THE FEASIBILITY OF THE USE OF OVERHAUSER EFFECT IN A NUCLEAR FREE PRECESSION MAGNETOMETER

DAVID L. COOPER

THE FEASIBILITY OF THE USE OF OVERHAUSER EFFECT IN A NUCLEAR FREE PRECESSION MAGNETOMETER

* * * * *

David L. Cooper

THE FEASIBILITY OF THE USE OF OVERHAUSER EFFECT IN A NUCLEAR FREE PRECESSION MAGNETOMETER

by

David L. Cooper

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1959

THE FEASIBILITY OF THE USE OF

OVERHAUSER EFFECT IN A NUCLEAR

FREE PRECESSION MAGNETOMETER

by

David L. Cooper

This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

from the

United States Naval Postgraduate School

ABSTRACT

Nuclear Free Precession Magnetometers have been in use since the first successful one was built in 1954. These magnetometers, used to measure the magnitude of the Earth's magnetic field, operate on the relationship that exists between the magnitude of the environmental magnetic field and the frequency of precession of the hydrogen nuclei placed in this field. One of the serious problems that is encountered in the present magnetometers is that they require a strong constant magnetic field, several hundred times that of the Earth's field, to gain the initial conditions for operation. To remove any possible perturbations caused by this large constant field, other means of obtaining the initial conditions were searched for. This paper explores one of the possible solutions to the problem. By using the Overhauser effect, the population gain of favorable proton states may be obtained by exciting the electrons of the free radical $ON(SO_3)_2^{--}$ and then using the spin-spin coupling of energy to the proton of the aqueous solution. This will provide a large favorable proton population without the attendent large constant field.

The author wishes to express his appreciation to Varian Associates, to Drs. Martin Packard and Weston Anderson of Varian Associates, and especially to Professor Carl E. Menneken of the U. S. Naval Postgraduate School for his encouragement and guidance.

TABLE OF CONTENTS

TABLE OF CONTENTS

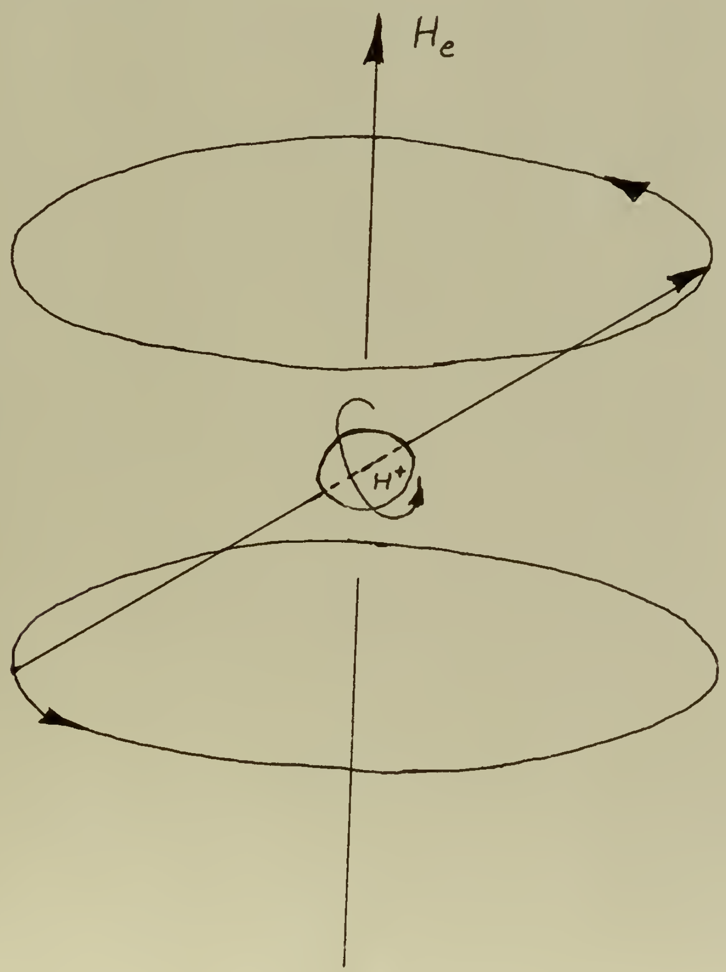
LIST OF ILLUSTRATIONS

1.0 Theory

To understand the phenomenon of nuclear resonance one must first look at the "hypothetical" proton, a small electrically charged mass rotating about its' spin axis in such a manner as to form a small electro-magnet. The spin is oriented to the environmental field determined by the quantum number "m". The proton is allowed two states,

$$m = \pm 1/2 \tag{1}$$

As the spin axis is offset from the environmental field, the magnetic dipole formed by the small spinning charge is also offset from the environmental field.



Hypothetical Model of a Proton

1.1 Theory of Nuclear Spin

From simple mechanics, it is seen that if there is a small magnet located in a relatively strong magnetic field, the small magnet will normally tend to align its' dipole axis to the direction of the field. Pake[10] draws the analogy between the proton and a spinning top. Recalling that when the force of gravity pulls on the spinning top, the top does not fall over. Rather the top precesses about it's precession axis. Likewise, as the proton is a small spinning mass, the force acting upon the proton, caused by proton's magnetic dipole attempting to align itself to the environmental field, will cause the proton to precess about the proton's precession axis. As no work is done, the proton will continue to precess about the environmental field indefinitely.

1.2 Useful Populations

From the fact that there are two spin states possible, it follows that some of the protons will have their precession axis aligned with the environmental field while the remaining protons will have their precession axis in the opposite direction to the environmental field. If it is assumed that there are N protons per cubic centimeter, then part of the protons, N^+, will be aligned to the field, while the remaining number, N^-, will be against the field. It can be shown[11] that the polulations are governed by a Boltzman distribution in the following relationship:

$$(2) \quad \frac{N^+}{N^-} = e^{\frac{2\mu H}{kT}}$$

where $N^+ + N^- = N$

μ = magnetic moment

H = environmental field

k = Boltzman constant

T = temperature (absolute)

If H is the Earth's field and T is the normal room temperature, one finds that the difference in populations is very small.

As the proton is a small magnetic dipole, rotating about the precession axis, it can be readily seen that if an infinitesimally small coil could be built so that the coil would surround only one proton, an electrical voltage would be generated in the coil. The frequency of this voltage is called the Larmor frequency. The United States Bureau of Standards has experimentally evaluated the relationship between the environmental field and the frequency of the oscillating voltage and standardized it as follows:

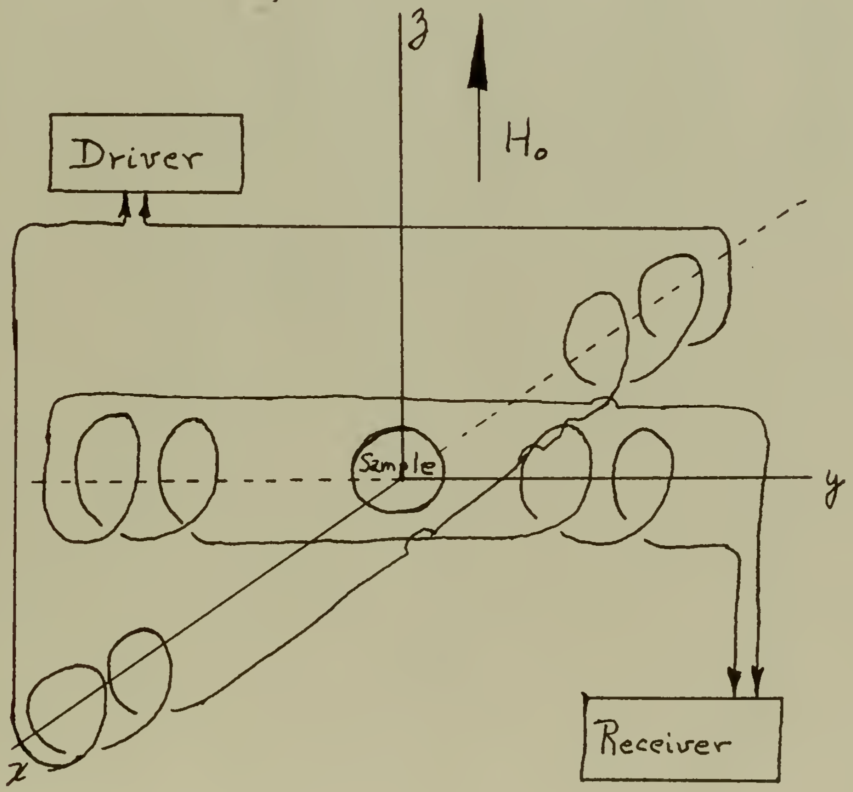
$$(3) \quad H = 23.4868 f_p$$

where f_p = Larmor frequency in cps
H = environmental field in gamma (1 gamma = 10^{-5} gauss)

It might be reasoned that if the number of protons were doubled, the signal would also be doubled. This, however, is not true. As there is random orientation of the protons' spin axis about the precession axis, any finite number included would tend to cancel out each other's signal and the net result would be noise. In addition, equation (2) shows that there are almost as many protons aligned against the field as with it and thus the "net" magnetic moment of several protons, considered in diametrically opposite directions would be extremely small. Recalling the parameter H in equation (2) and noting that when it's value is increased, the usable population N^- is increased. This still leaves the problem that the protons within the population N^- are still randomly oriented with respect to each other about the environmental field H.

1.3 Nuclear Magnetic Resonance

Historically, Bloch, Hansen and Packard(1) and separately Purcell, Torrey, and Pound(2) were the first to take advantage of Nuclear Resonance and for their work Bloch and Purcell were jointly awarded the Nobel Prize in 1952. The work of Bloch, Hansen, and Packard is of more interest to this paper due to the methods used. Bloch employed two coils so oriented as to reduce the mutual coupling "M" as much as possible. The proton was used as the coupling device between these coils. Figure 2 shows the arrangement of these coils.



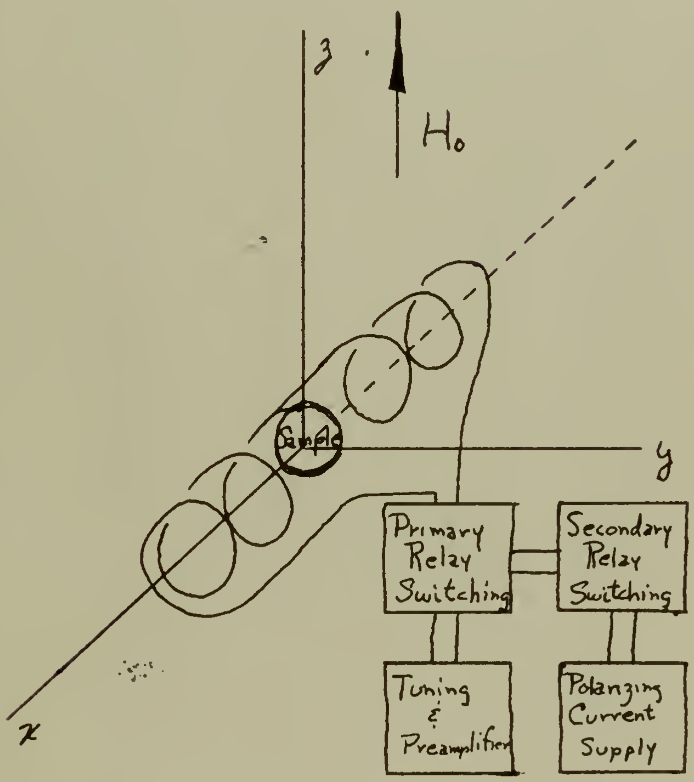
Position of Driver and Receiver Coils

Into one coil, called the transmitter coil, is put a driving signal at the Larmor frequency as obtained from equation (3). When a sample of water, which contains many protons, is placed within the pair of coils, the protons are driven in unison and thus considerations are no longer restricted to one proton but rather applies to many. This large "phase-locked"[3] population now provides a relatively large magnetic moment vector in the classical sense which while precessing will generate a very weak signal in the second coil, called the receiving coil. Eventually the protons will loose phase coherence as they revert to random orientation in their precessing about the driving field. This is a very simple explanation of the experiments carried out by Bloch. In his paper, Bloch suggested that if some other means could be found to initiate the coherence the protons might be made to precess freely on their own.

1.4 Nuclear Free Precession Magnetometer

In 1948, Russell Varian[8,15] conceived and patented the idea of the "Nuclear Free Precession Magnetometer" in which the population of N^+ was obtained by the use of a several hundred gauss field which would be oriented perpendicular to the Earth's field. By cutting off this polarizing field rapidly, many of the protons would commence precessing in phase about the Earth's field. If another coil, perpendicular to both the Earth's field and to the polarizing field, were placed around the sample, it would then pick up the signal generated by the coherently precessing protons. It was not until 1954 that members of the Varian research staff applied Russell Varian's idea and built the first operating "Nuclear Free Precession Magnetometer". In the early experimental models the two coil approach was used. In the present models of the

magnetometer, the same coil is used for both polarizing and detection. This can be done by switching the coils from the polarizing current source to the detector thru a carefully worked out current damping network. The general arrangement of the circuits for the single coil magnetometer is shown on Figure 3.



Block Diagram of Single Coil Magnetometer

1.5 Difficulties of Removing Polarizing Field

One of the principal difficulties encountered in the Nuclear Free Precession Magnetometer is that of removing the polarizing field with optimum speed. This removal has to be accomplished within an interval short compared to several periods of the Larmor frequency. If the current is underdamped, it will oscillate back and forth several times.

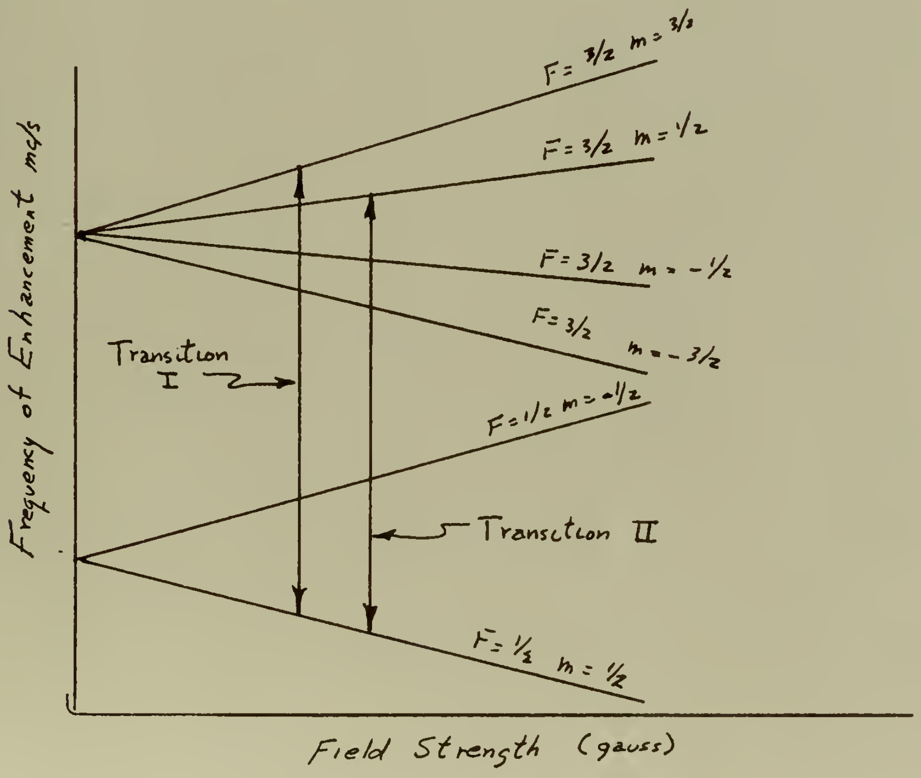
If the frequency of oscillation is higher than the Larmor frequency, the protons will be uneffected by the oscillatory field generated. If the frequency of oscillation is lower than the Larmor frequency, the protons will tend to follow this field and thus destroy the initial coherence. If the current is overdamped, the protons will remain sligned to the decaying field and as the field decays so will the population N^+. It is therefore desired that the current be damped as quickly as possible without oscillations, or in other words, critically damped.

There are several problems that the designers of magnetometers would like to overcome. One of these is the problem of critically damping the polarizing current. A second problem is the large attendant fields associated with the heavy polarizing current. Another problem is the large power supply necessary to provide the polarizing current. The designer is continuously looking for other methods that will provide the desired population difference without using the large polarizing field.

1.6 Overhauser Effect In $K_2ON(SO_3)_2$

While looking for various paramagnetic compounds that exhibited nuclear magnetic resonance, Lllyod and Pake[19] found that the free radical, peroxylamine disulphonate ($ON(SO_3)_2^{--}$) exhibted an Overhauser effect in which energy could be given to the electrons of the free readical at the electrons Larmor frequency, and thru various relaxation processes, the various nuclei population N^+ could be increased. One of the relaxation processes investigated was that of the spin-spin coupling of the electron to the protons of the aqueous solution of Potassium peroxylamine disulphonate. At the field intensities that they were using and for the frequencies used, Llyode and Pake considered that this particular relaxation process had a small probability of occurrence as compared to the others investigated.

The work of Llyod and Pake led Abragam, Combrission, and Solomon[5] to do further research with the particular free radical peroxylamine disulphonate. Their work showed that the spin-spin coupling between the electrons and the protons, previously thought to be of little consequence was of more importance at lower field intensities. The Overhauser effect exhibited proved to be capable of giving the desired population increase. While studying the effect at both fields and in the Earth's field, Abragam built a "Maser" type magnetometer in which the population difference was gained from the Overhauser effect and by a careful scheme of positive feed-back amplifiers a stable oscillator could be made to run. The frequency of this oscillator was dependent only on the magnitude of the environmental magnetic field.



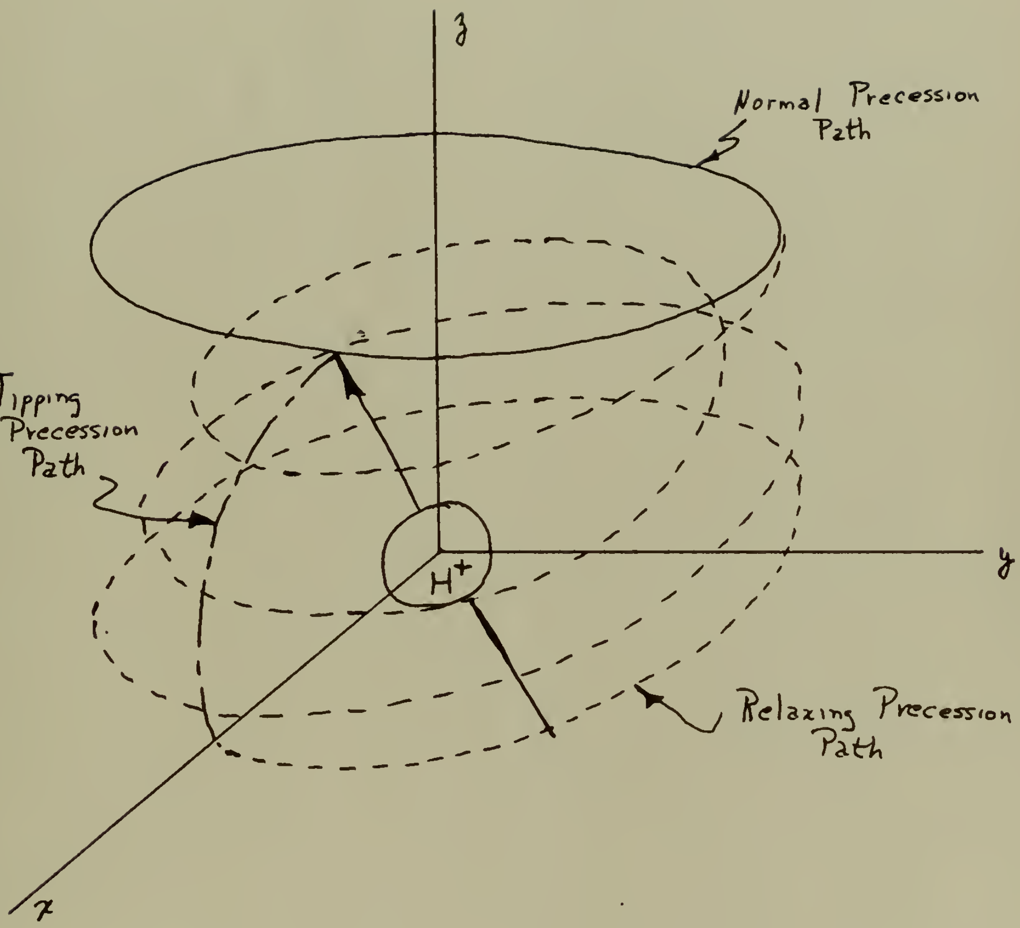
Modified Breit-Rabi Diagram

1.7 Frequencies of Enhancement

From a modified Breit-Rabi diagram[20], it can be shown that the frequency at which the electron is excited is 55 mc/s for a zero magnitude field and that it increases linearly (in fields that are of interest for this paper) at the rate of 2.8 mc/s per gauss of environmental field for Type I transitions and 1.9 mc/s per gauss of environmental field for Type II transitions. Type I transitions take place when the electron exciting or enhancing field is perpendicular to the environmental field. Type II transitions take place when the enhancing field is parallel to the environmental field. Figure 4 shows these relationships.

1.8 Other Methods Of Obtaining Initial Coherence

As was pointed out earlier, the initial coherence for the original Nuclear Free Precession Magnetometer was obtained by orienting the precession axis of the protons at approximately 90 degrees to the Earth's field while at the same time increasing the population N with the large polarizing field. If the polarizing field is aligned to the Earth's field, the protons will continue to precess about the Earth's field without coherence when the polarizing field is removed. Regardless of how the desired population difference has been accomplished, if a second field is now applied, which shall be referred to hereafter as the tipping field, perpendicular to the Earth's field, the spin axis of the protons will precess about the resultant of the tipping field and the Earth's field. If in the case of a constant magnitude tipping field, the magnitude is in the order of from two to five gauss as compared to the nominal value of one half gauss for the Earth's field, the resultant field will be approximately perpendicular to the Earth's field and about equal in magnitude to



Paths of Precession

the tipping field. The duration of the application of the tipping field should be such that the spin axis will be allowed to precess only 90 degrees. When the tipping field is removed, the proton will be influenced by the Earth's field only and will now precess about it eventually spiralling back to the normal precession path. This type of polarization, or more correctly orientation, is called $\pi/2$ polarization.[22]

This same form of $\pi/2$ polarization may also be accomplished in another manner. Recalling that in the original work of Bloch, Hansen, and Packard there was an arrangement of coils similar to that now suggested. The strong magnetic field that produced the environmental field and also the required population difference is now replaced by a polarizing field in the same direction as the Earth's field. This will now provide the necessary population difference but not the correct orientation. The tipping field will replace the driver field which is at the Larmor frequency. When the polarizing field has been shut off, the Larmor frequency tipping field is turned on. This causes the protons to commence precessing about the tipping field, in a plane perpendicular to the axis of the tipping field. The Larmor frequency field is left on until the proton has precessed exactly 90 degrees, at which time the tipping field is removed. The only field that now has effect on the proton is the Earth's field and the proton will precess about the Earth's field, slowly realigning itself to the original angle that it made with the Earth's field.

It is often easier to think of the total magnetic moment vector rather than the individual proton. This vector grows in magnitude as more protons are put in the favorable population state. After polarization, the vector has reached it's greatest magnitude. The vector will

then begin to decrease in magnitude exponentially, obeying the equation:

$$(4) \quad M = M_o e^{-t/T_2}$$

T_2 is the decay constant. This constant can vary depending on the source of protons. In pure water, for example, T_2 is normally about two to three seconds. As various "relaxers" are added to the pure water, the time constant T_2 is decreased, becoming as short as one quarter second or less. Ferrous Chloride is one such relaxer. Any other salt that exhibits para magnetic properties when in aqueous solution will cause the same effect.

1.9 Definition of T_1, T_2, etc.

Another constant that is important is T_1. This is the time associated with the growth of the magnetic moment vector. The relationship is as shown in equation (5).

$$(5) \quad M = M_o \left(1 - e^{-\frac{t}{T_1}}\right)$$

Normally T_1 is greater or equal to T_2 in magnitude. One of the points of interest in this experiment was to determine if T_1 can be made smaller than T_2 by the relaxation process of the spin-spin coupling of energy from the electron to the proton.

2.0 Experimental Procedure

For the purposes of this thesis, it was suggested by Dr. Martin Packard of Varian Associates than an investigation of a "Nuclear Free Precession Magnetometer using the Overhauser Effect" be investigated for feasibility. The Nuclear Free Precession Magnetometer using the Overhauser Effect would be a version of the normal Nuclear Free Precession Magnetometer wherein the "polarization" is accomplished by Overhauser enhancement rather than by the large constant fields that are used by Varian Associates in their present magnetometer.

2.1 Methods of Attack

Several methods of attack were open to the investigator:

(1) Enhance in the Earth's field and then tip the spin axis by a constant field $\pi/2$ pulse.

(2) Enhance in the Earth's field and then tip the spin axis by a Larmor frequency $\pi/2$ pulse.

(3) Enhance in an "orienting field" and then rapidly remove the orienting field as in the case of the normal magnetometer.

2.1.1 Polarization, Constant Field

Method (1) required that the enhancement of the population be done in the Earth's field. This presents no expected difficulties as this would be done at a frequency of about 55.2 mc/s. As outlined in Appendix A, the product of the field intensity H_r and the duration of the tipping field pulse t_t, is a constant. As the desired resultant field should be approximately perpendicular to the Earth's field, the tipping field should be approximately two and one half gauss in magnitude. This will cause a resulting field also of two and one half gauss in magnitude offset from

the Earth's field by 79 degrees. Referring to Figure 19 of Appendix A, it is easily seen that this would require the pulse current to be 166 milliamperes for a duration of 22 microseconds. This was considered to be too difficult to obtain when more direct methods of orientation were available.

2.1.2 Polarization, Larmor Frequency Field

Method (2) presented a simpler approach to the problem. Referring to page 12, it is again noted that the arrangement of coils used for Method (2) is basically the same as for the origional work of Bloch. One of the assumptions that Bloch made was that the driving, or in this case tipping field, be small as compared to the environmental field. As the magnitude of the environmental, or Earth's field is approximately one half gauss, this would require that the tipping field be in the order of 50 milligauss or less. From Figure 19 of Appendix A, this magnitude field would require a current of 35 milliamperes or less, which is easily accomplished and just as easily removed. As the magnitude is not critical, except that it be small as compared to the Earth's field, it would appear that it might be better to arbitrarily select the duration of the field and adjust the magnitude rather than select the magnitude and adjust the duration as in Method (1). Desiring to avoid problems of transients and to insure that there was a reasonable number of Larmor cycles present, the duration was chosen as ten milliseconds. This will allow the pulse to contain approximately twenty cycles. From Figure 19 of Appendix A, it is seen that the Larmor frequency peak current should be 380 microamperes. This value of current could be obtained easily from a transistorized audio cmplifier and could also be damped out easily without destroying the coherence of the protons.

In going from a constant field pulse to a Larmor frequency oscillating field pulse, pulse duration is less critical and there is less difficulty in removing the current pulse. However, there is now the added complexity of keeping the frequency correct. This would require that there be a memory unit which would store the frequency obtained from the preceeding cycle and use this stored knowledge to correctly tune the Larmor frequency oscillator for the present cycle. Due to this added complexity it was thought that it would be better to investigate Method (3) prior to attempting to implement Method (2)

2.1.3 Enhancement in Orientating Field

Method (3) is in many respects a simplified form of the normal Nuclear Free Precession Magnetometer. In this method the Overhauser enhancement takes the place of the strong polarizing field for the purpose of obtaining the favorable population N^+. To provide orientation of the spin axis of this favorable population, a small constant field is produced perpendicular to the Earth's field. Recalling that a field of about two and one half gauss will accomplish this desired effect, if it is perpendicular to the Earth's field, it was decided that this field could be generated most easily in the same coils that were to be used for detection. Thus, with the single exception of the additional enhancement circuit, the circuitry for Method (3) is identical to that for the normal magnetometer.

From Figure 4 it can be seen that the frequency for enhancement is given by:

(6) $f_e = 55 + 2.8H$ Transition I H in gauss

(7) $f_e = 55 + 1.9H$ Transition II f in mc/s

Thus with a two and one half gauss field, the frequency for enhancement is 62.14 mc/s for Transition I and 59.84 mc/s for Transition II.

As Method (3) required only the addition of the enhancing circuitry to that of the existing magnetometer, this method was chosen as the one for initial investigation. If time permitted, Methods (2) and (1) were to be investigated in that order.

2.2 Programming of Time Schedule

Figure 7a and 7b shows the various timing programs for the system. Program A is for Methods (1) and (2), while Program B is for Method (3).

From Figure 7a it can be seen that such times as t_o, t_1, t_2, t_3, t_4, and t_5 can all be varied over a considerable interval of time. It was proposed that initially the period of the t_o to t_o cycle be made six seconds. This conformed to the cycle rate of one of the timers of the Varian station magnetometers. In Program A the period t_o to t_1 was variable from zero to three seconds. The periods t_1 to t_2, t_3 to t_4, and t_5 to t_o were due to the setting of secondary cams and also to various secondary relays. The period t_2 to t_3 was due to a tertiary relay pair. The delay in initiating one part of the cycle after the preceeding part was to allow the generated transients to die out.

In Program B, the period from t_o to t_1 was also variable from zero to three seconds. Again the periods t_1 to t_2, and t_3 to t_o, were controlled by secondary relays.

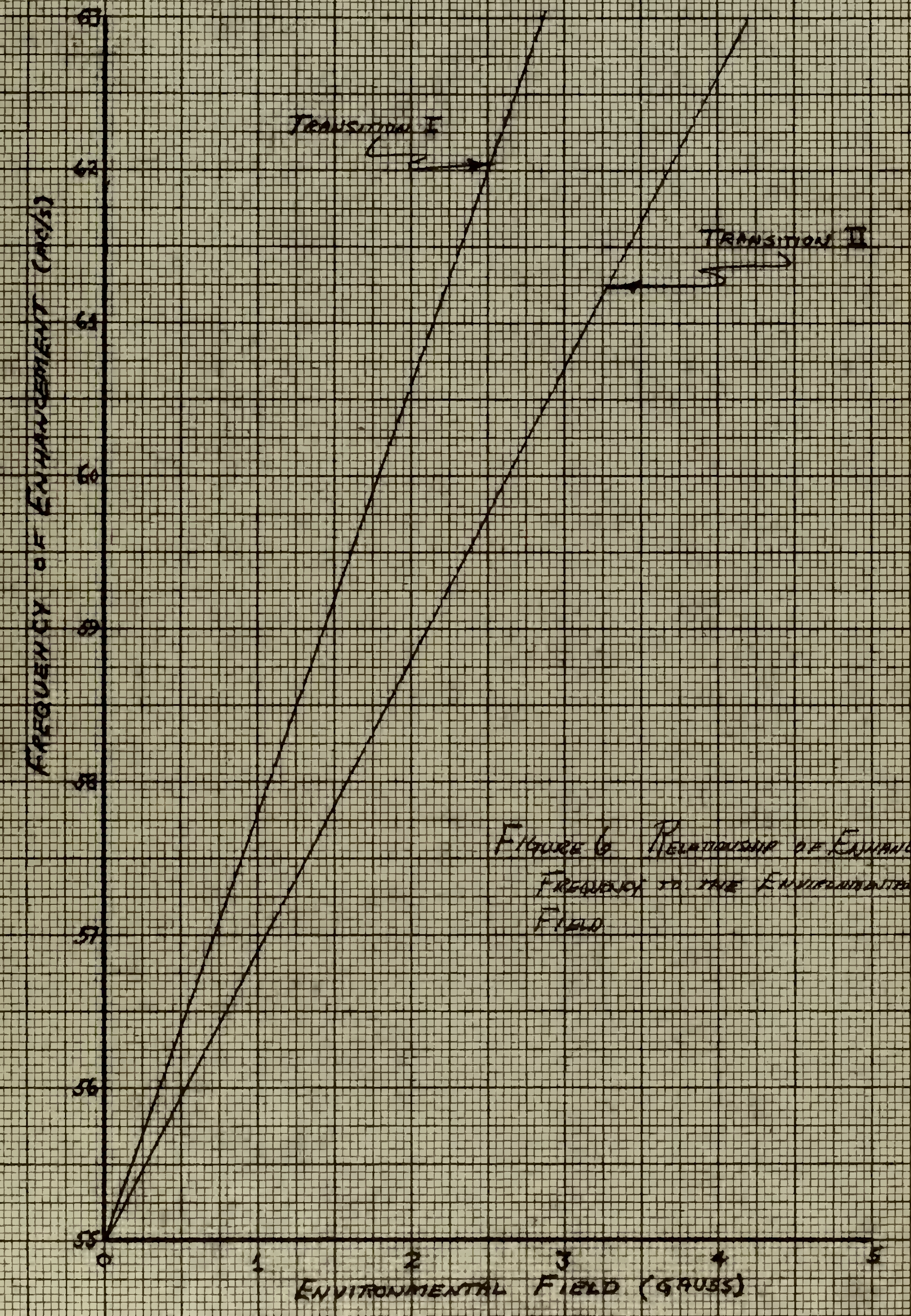


Figure 6 Relationship of Enhancing Frequency to the Environmental Field

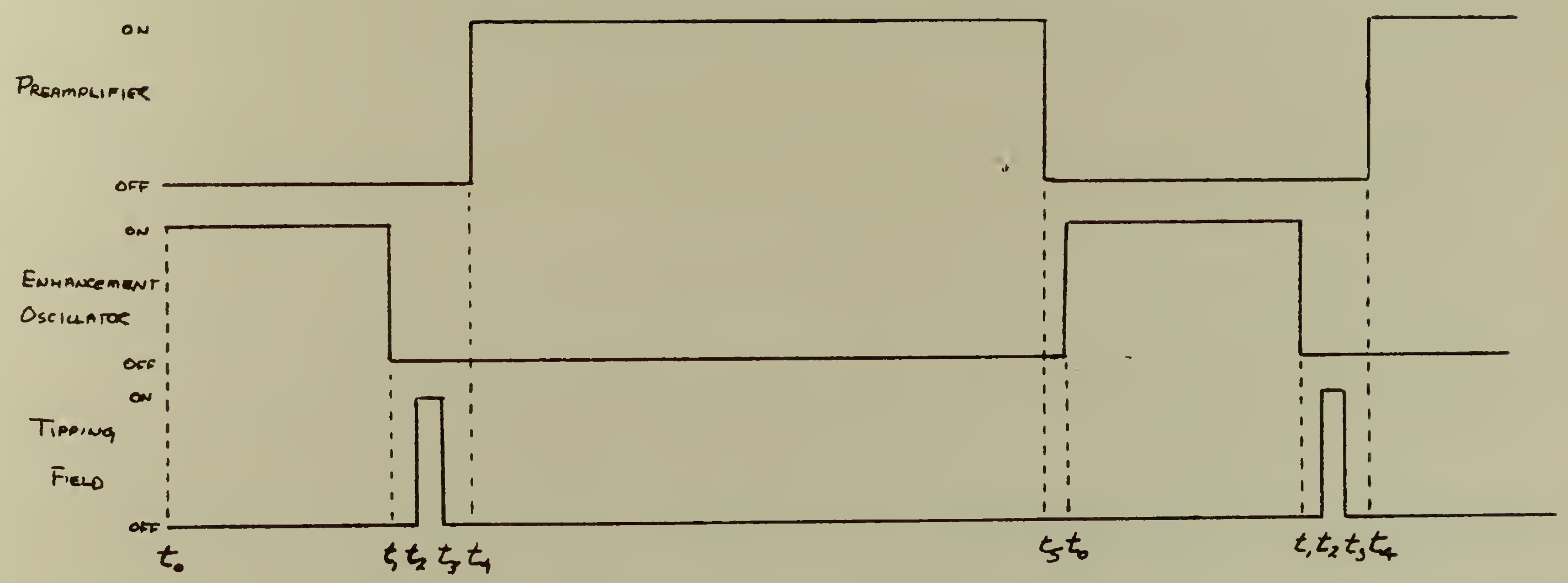


FIGURE 7a PROGRAM A TIMING SCHEDULE

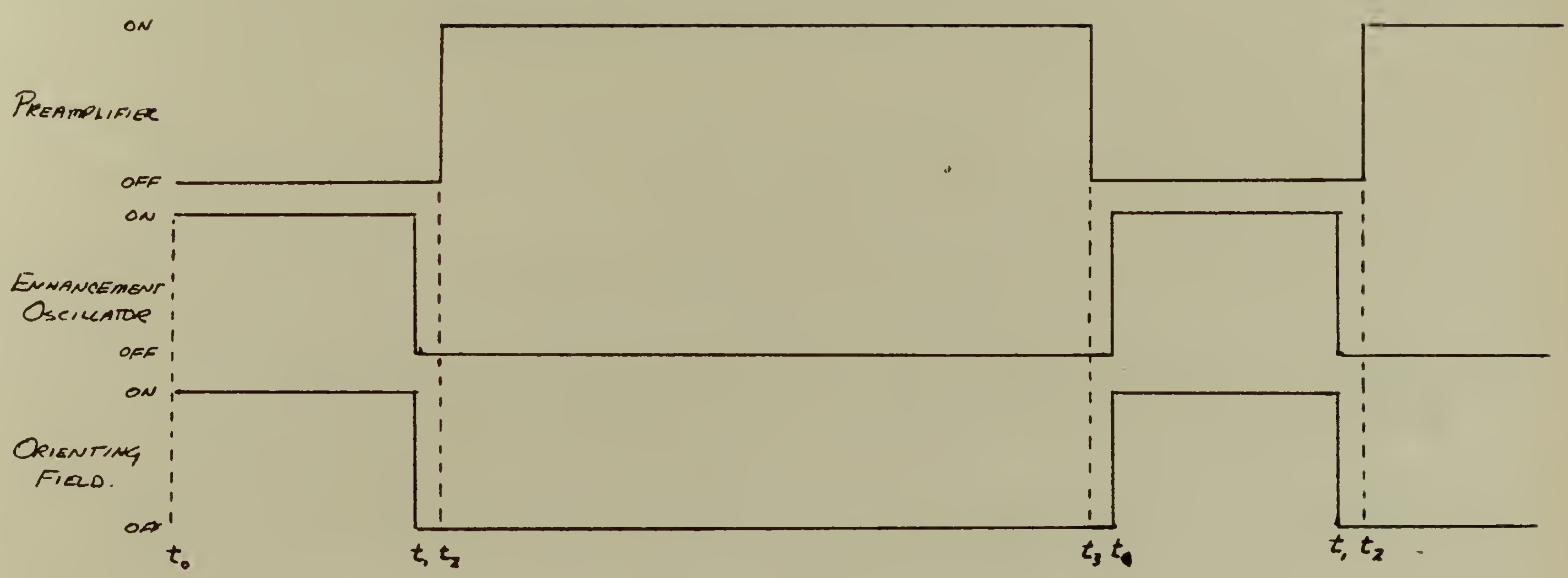


FIGURE 7b PROGRAM B TIMING SCHEDULE

Once initial operation of the magnetometer was accomplished successfully, the timing circuits were to be switched to those used with an older model magnetometer. This magnetometer had two cycling rates, fast and slow. For the fast rate, the period t_0 to t_1 was one quarter second. For the slow rate, the period t_0 to t_1 was one half second. The period t_4 to t_5 in Program A and the period t_2 to t_3 in Program B was controlled by the slow counters. The complete cycle was controlled by a free running multi-vibrator with a period of 1.2 seconds for the slow cycle and 0.7 seconds for the fast cycle. In addition to the normal operation of the multi-vibrator, it could be recycled by a pulse from the slow counter. Upon receiving the 256 count pulse on the fast cycle or the 512 count pulse on the slow cycle, the multivibrator flips to the polarize (or orient, enhance etc.) portion of the program.

The sample to be used was a 0.005 molar solution of $K_2ON(SO_3)_2$ buffered to a ph of about 11 with a saturated solution of Na_2CO_3. This solution was put in a Varian NMR Spectrometer and the time of relaxation, T_2, was found to be 0.6 seconds. Since T_1 and T_2 are approximately equal, T_1 is also approximately 0.6 seconds. For maximum output signal, the time of polarization should be in the order of five T_1 or in this case about three seconds. It was decided that once the Nuclear Free Precession Magnetometer with Overhauser Enhancement was made to run, the period $t_0$tto t_1 would be shortened progressively until no output signal was detectable.

3.0 Experimental Equipment

Figure 8 shows a block diagram of the complete system. The blocks remain the same regardless of which method of operation is employed. The internal parts of the various black boxes may be modified as necessary between the different methods.

3.1 General Outline

The detection coils form one of the more critical parts of the system. These coils pick up the very weak magnetic signal of the precessing protons and transform it into an electrical signal by generator action. The output signal from the coils is normally in the order of microvolts. This signal is fed thru a tuning circuit into a pre-amplifier where it is then amplified approximately one hundred and twenty db. The bulk tuner further decreases the bandwidth thus increasing the signal to noise ratio. The amplifier-limiter prepares the signal for the slow counter, by squaring the sine wave of the precession signal. The slow counter then counts the cycles of the Larmor precession frequency. The output of the slow counter operates a gate which allows the 800 kc/s standard frequency to pass into the fast counter. The slow counter has two outputs that affect the gate, 256 counts or 512 counts. On the fast cycle, the gate is open for 256 counts of the precession frequency while in the slow cycle the gate is open for 512 counts of the precession frequency. The binary information from the fast counter is analoged to operate the bulk tuner and also to give a signal to the output recorder.

Block Diagram

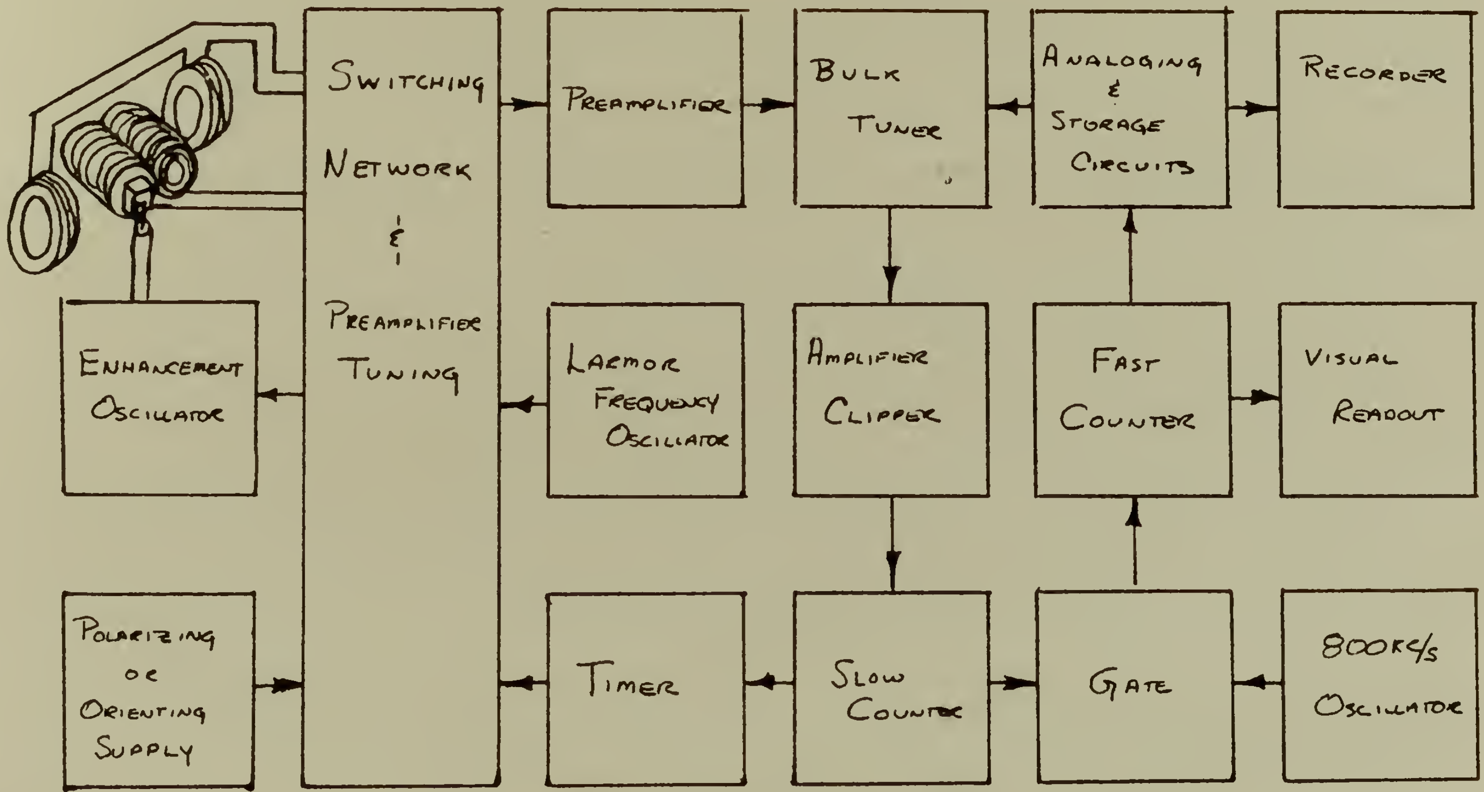


Figure 8

In addition to gating the fast counter, the slow counter also triggers the cycle control multi-vibrator. This provides that there is no lost time after the desired count of the precession frequency is completed. The cycle control multi-vibrator operates the relay switching network which in turn makes the appropriate connections between the detection coils and the tuning network or the polarizing (or orienting) supply. The switching network also controls the operation of the enhancing oscillator and the tipping coil.

3.2 Polarize Current Supply

In the case of the normal magnetometer, the polarizing supply was capable of eighty amperes of direct current. It was found that when this supply was used for the orienting field current supply, the ripple was too great to be tolerated. A well filtered transistor power supply capable of 300 milliamperes was sutstituted for the higher capacity current supply. This transistorized power supply proved perfect for the purposes.

3.3 Timing and Damping Networks

The timing relays operate as shown in Figure 9. The master relay, K1, is nothing more than a switch which is controlled by the cycle control multivibrator to operate the remaining relays. When the system is run on the standard station magnetometer mechanical clock, the connections to K1 are broken at point 1 and the micro-switches of the clock are then connected in series to actuate the remaining relays. When K1 closes it provides a circuit to close K2. K2 in turn provides the circuit to close K3. However, due to the capacitor, resistor, diode network paralleling the coil of K3, there is a time delay of approximately 150 milliseconds.

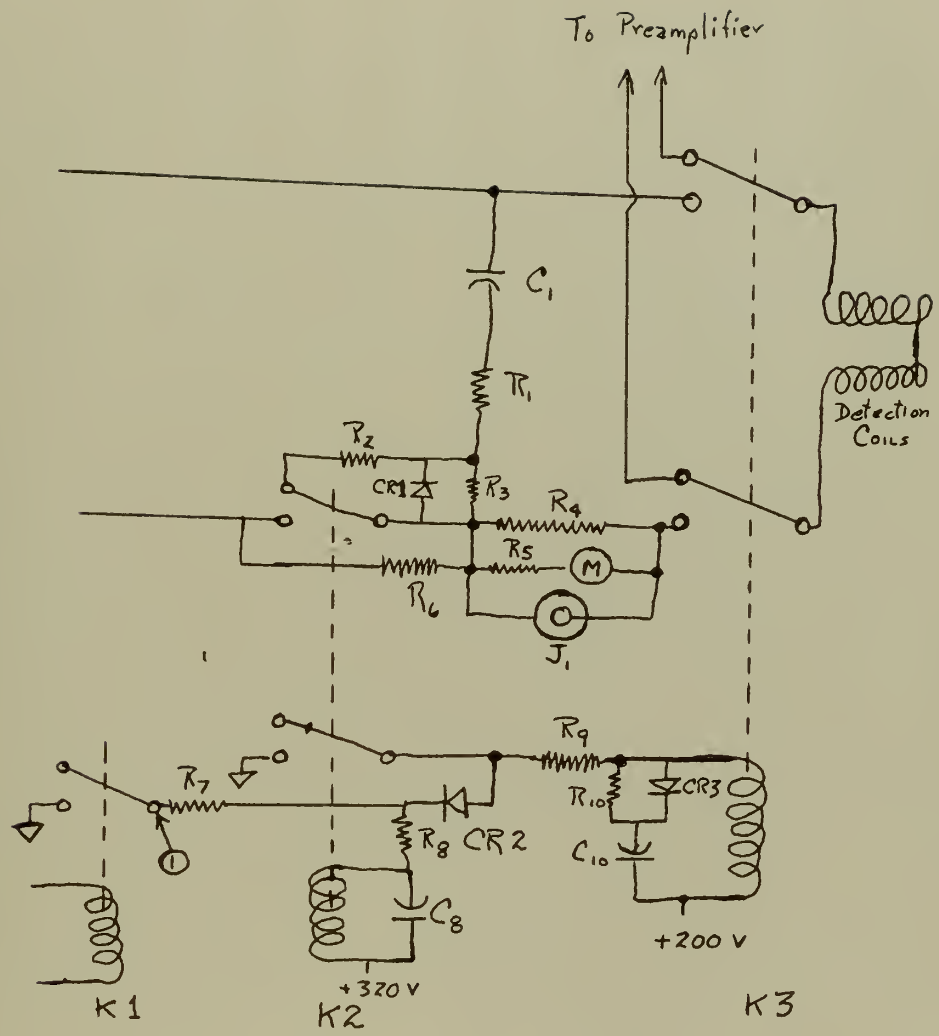
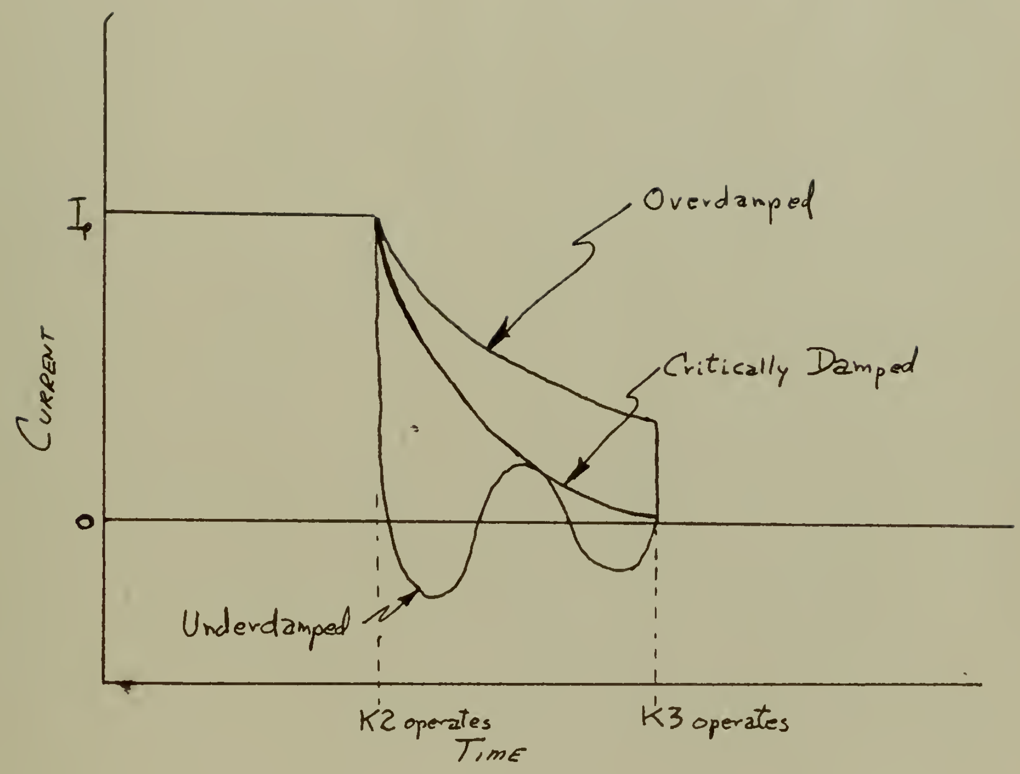


Figure 9 Current Damping Circuits

This time delay was built into the origional magnetometer to allow the current flowing in the detection coils to be critically damped. When K3 finally closes it removes the detection coils from the damping circuit and connects them to the tuning circuit of the pre-amplifier. A typical current waveform as seen at J1 is sketched in Figure 10, for the normal operation.



Current Waveform

As the magnitude of the current flowing thru the detection coils during the polarize portion of the cycle is varied, the magnitude of capacitor C_1 must also be varied to maintain critical damping. The higher the value of current the larger C_1 must be. At two amperes of polarizing current 150 microfarads of capacitance are needed for critical damping. At ten amperes of polarizing current, 650 microfarads of capacitance were needed for critical damping. By interpolation it may be seen that little or no capacitance would be required for critical damping if the current was in the order of ten to one hundred milliamperes. This proved to be the case when the experiment was actually run.

3.4 Detection Coils

The detection coils used were two that had been wound earlier for another experiment. These were of the proper size to fit around a four ounce polyethylene bottle. A pair of coils identical as to turns, cross-sectional area etc., were used as a noise cancelling arrangement. This can be seen from Figure 11, if the direction of the windings is taken into consideration. It can be seen that a noise generated magnetic field, $\Delta \vec{B}$, that is increasing in magnitude to the left in both coils as shown by the arrows, will cause a current to flow in the coils as shown by the arrows. It is now readily apparent that these currents are flowing in opposite directions thru the same path. If the field that is causing the currents is constant in direction and magnitude over the volume occupied by the two coils, then these currents will also be equal in magnitude and will thus cancel each other out. It should also be noted that if the polarizing or orienting current were to pass thru the two coils, the direction of the field generated would be in opposite directions and thus the signal from the protons in the sample in each coil would tend to add thus increasing the signal. Thus, it can be easily seen that the magnetic noise generated is reduced, the signal received is increased, and therefore the overall signal to noise ratio is increased. To prevent electrostatic noise from being introduced into the detection coils, a Faraday shield would normally be used around the detection coils. In addition, due to the presence of the enhancing coils inside the detection coils, it is necessary to place a Faraday shield on the inside of the detection coils also. The detection coils each had ten layers of 53 turns of number 15 enameled copper wire for a

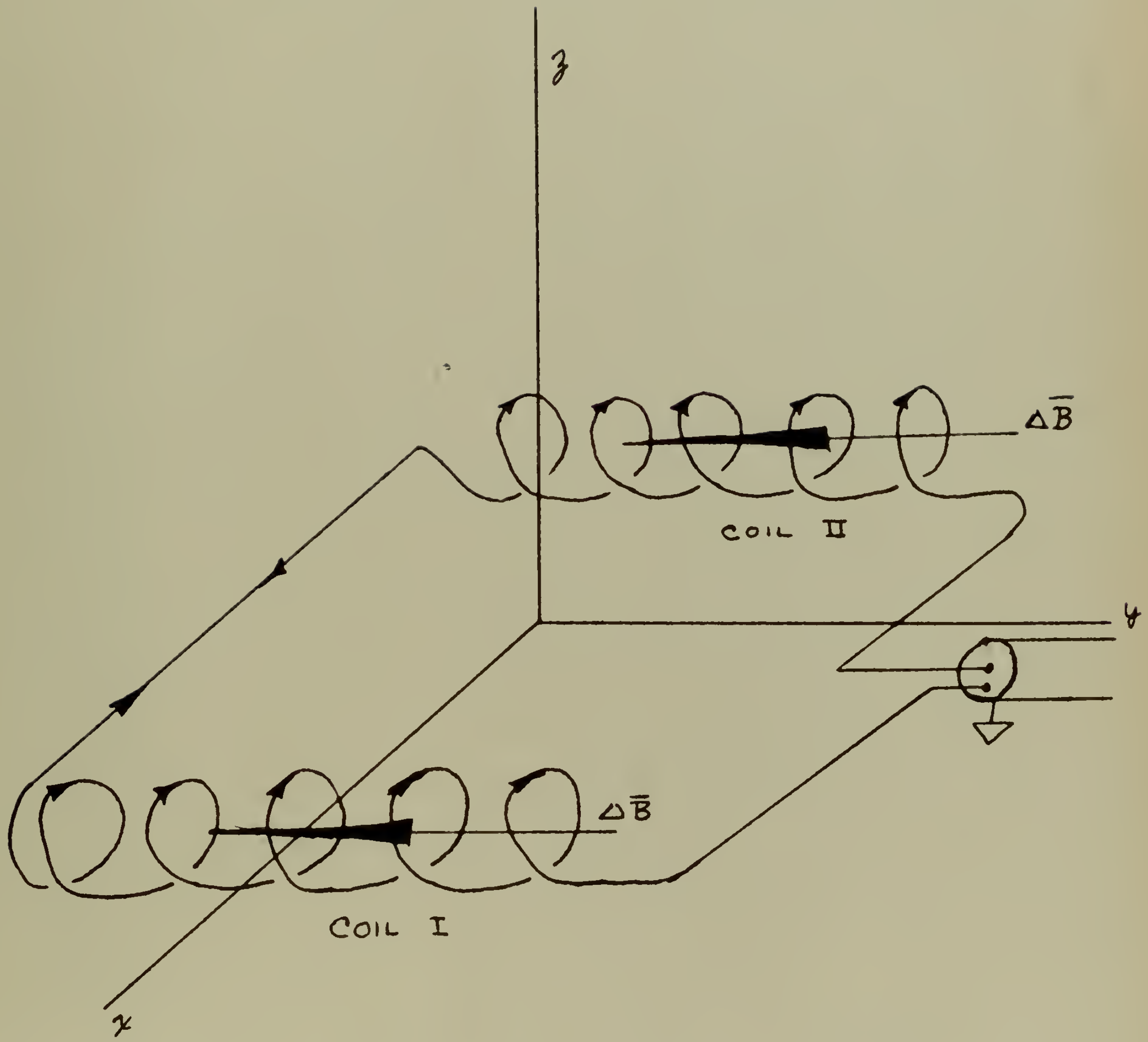


Figure 11 Detection Coils

grand total of 530 turns. The inside diameter was two inches which allowed about one eighth inch clearance between the bottle and the coil. Each coil had an inductance of 23.11 millihenries and a Q of 31. Thus, the total inductance of the two coils in series was 46.22 millihenries and a Q of 31.

3.5 Enhancement Coil

The enhancement coil consisted of a single turn of number 15 enameled copper wire enclosed in a three millimeter glass tube. The glass tube insulation was made necessary by the fact that the heat generated by the coil melted the origional polyethylene insulation and caused plastic flow. This plastic flow allowed the solution to leak out around the joint between the insulation and the bottlecap and form a conducting path across the coil. This conducting path effectively shorted out the enhancing signal. The glass tube was bonded to the phenolic cap with an epoxi resin which formed a strong liquid-proof seal. In air alone, the enhancing coil had an inductance of 0.209 microhenries while in the sample solution the inductance increased to 0.218 microhenries while the Q of the coil decreased from 140 to 28 under the same conditions. There was an additional slight decrease in Q by placing the sample bottle with the enhancing coil, inside the detection coil.

As the enhancing coil was to be fed from a 50 ohm coaxial cable, the coil had to be matched to the cable. Computations for the matching may be found in Appendix B. As only one sample bottle was to be used initially, due to the requirements of Methods (1) and (2), it was not necessary to match two coils to the 50 ohm cable. At a later date after the initial experiment was successful, it was necessary to match two coils to the 50 ohm cable. This simply means that for purposes of

computation, the total inductance is now doubled and the matching equations are now recomputed.

3.6 Enhancement Oscillator

The enhancement oscillator was designed to be capable of delivering 50 watts to a 50 ohm co-axial cable. The oscillator is in effect a free running multi-vibrator with an inductance as the plate load. These plate inductances are coupled with an "M" of large magnitude so that their fluxes aid in each others coil. A single turn loop matches the cable to the tank. The oscillator is capable of a considerable power range. This is accomplished by using two different tubes and also by varying the B supply. The power transferred to the enhancing coil is controlled by the degree of tuning of the enhancement coil. If the tubes are 2E26's the oscillator is capable of 50 watts. If the tubes are 6146's, then the oscillator is capable of over 120 watts. The circuitry for the oscillator is shown in Appendix E, Figure 24.

3.7 Larmor Frequency Oscillator For Tipping Field.

Several different supplies were tried for the Larmor frequency pulse of Method (2). Initially, it was thought that this might be accomplished by the use of a nominal 1 kc/s oscillator which drove a frequency doubler and amplifier stages. The circuitry for this is shown in Figure 22 of Appendix E. The oscillator built was stable to one part in two thousand. Frequency control could be accomplished by using "Vari-caps" in parallel with capacitors C_1, C_2, and C_3. As the present method of tuning the bulk tuner is with relays cutting in and out various inductances and capacitances, it might also be feasible to tune the Larmor frequency oscillator with these same relays, by shorting out part of the resistors

R_1, R_2, and R_3. It was found out that the origional ideal of cutting off the stage Tr_3 and Tr_4 by changing the point of base bias voltage was not satisfactory as this required capacitor C_4 to charge or discharge as the bias point was changed. This left a large transient in the input to the amplifier that was not desirable. To avoid this, the transistors were emitter biased as shown in Figure 23.

The second method of obtaining the Larmor frequency desired was to use a standard audio oscillator which was set to the correct frequency. This could be done by comparing the Larmor precession frequency during readout to the frequency of the audio oscillator on an oscilloscope, getting a circular stable picture Lisajou pattern. This method was one that was actually used to attempt to get the magnetometer to operate by Method (2).

3.8 Pulse Duration Control.

Two methods of obtaining the pulse duration t_2 to t_3 in Program A were used. One consisted of a monostable multi-vibrator and the other was a pair of relays with an LC delay network in the coil circuit of one of the relays. The circuit of the monostable multi-vibrator is shown in Figure 23. This multi-vibrator had an on time of ten milliseconds. It could be triggered with a pulse of from ten to twenty volts negative. It was expected that this pulse could be obtained by connecting one of the screens of the enhancement oscillator to a voltage divider thru a small capacitor (in the order of 100 micromicrofarads). When the enhancement oscillator was shut off, the screen dropped 200 volts and thus the pulse desired is generated to trigger the monostable multi-vibrator.

The second method of obtaining the desired pulse duration was to use a pair of relays. These were connected as shown in Figure 12. When relay K3 closed, it closed both relays K4 and K5 and charging capacitor C. When relay K3 opened, K4 also opened but relay K5 was held closed by the capacitor, resistor, diode network for an additional ten milliseconds. It required that one relay was closed and the other open for a thru circuit to the tipping coils.

3.9 Tipping Coils.

The tipping coils were made in the configuration of a pair of Helmholtz coils. They were more than satisfactory when considered from the viewpoint of Method (1) in that they generated a strong field with a small value of current. They were not as useful from the viewpoint of Method (2) because for the weak field required, the current was so small that it was almost lost in the noise. They did however represent a compromise between the two methods. The sample along with the detection coils was placed in the center of the Helmholtz pair. This would then provide the field, perpendicular to both the detection coils and the Earth's field, necessary to obtain the desired $\pi/2$ pulse. If a sample were used in both of the detection coils, one would find that the signal obtained from one bottle would cancel that obtained from the other bottle. This is because the protons would have origionally been aligned to the Earth's field and those in each bottle would be tipped in the same direction and thus when they were released to precess freely would do so in the same direction. It has been shown

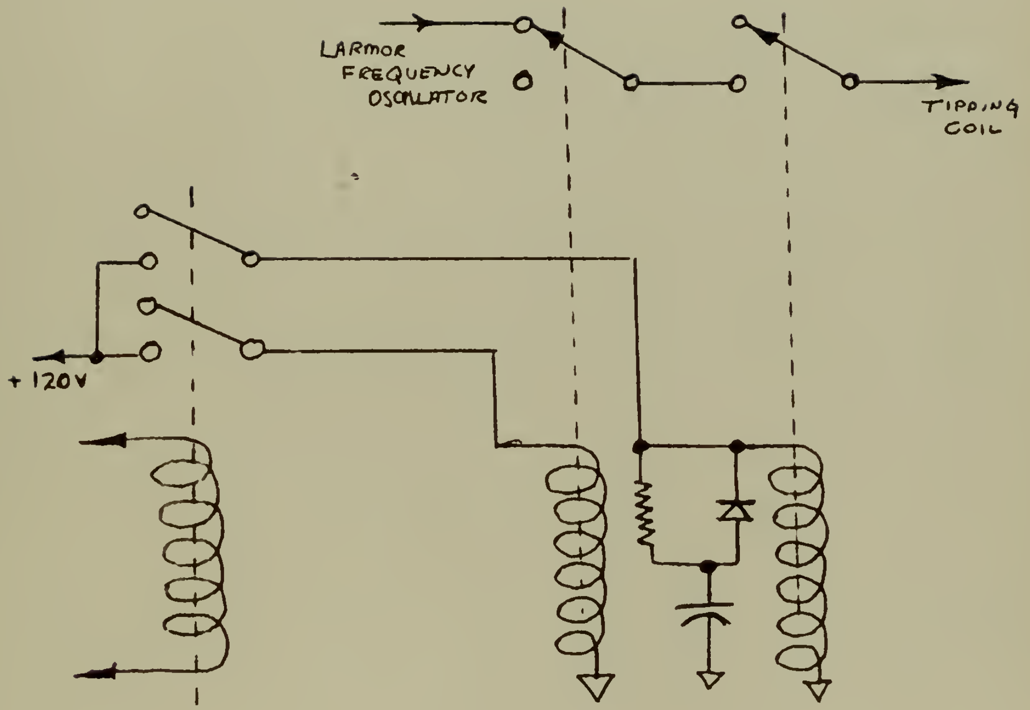


FIGURE 12 PULSE DURATION RELAY PAIR

previously that when the same field is present in both coils the signal from one coil will cancel that generated in the other. It might well be noted here that in the case of Method (3) the orientation is done in opposite directions and thus the signals will add. The computations for the design of the tipping coils are outlined in Appendix C. The two coils had a measured inductance of 87.75 millihenries and a Q of 59.

3.10 Fast Counter

The balance of the equipment is composed of components similar to those found in the Varian Associates Proton Free Precession AIRBORNE MAGNETOMETER Model V-4910. These components were used without modification and therefore need no further discussion with the exception of the fast counter. The principle that the fast counter operates on is one of interest because this is the heart of the accuracy of the magnetometer.

Remembering equation (3)

$$(3) \qquad H = 23.4868 f_p$$

one can quickly note that there is the problem of measuring the frequency f_p. Frequency may be measured accurately by counting the number of cycles observed during a known period of time. If one considers the period of time as T and the number of cycles counted as n, then these parameters are related to f_p by

$$(8) \qquad f_p = \frac{n}{T}$$

Likewise, the period of time may be related to a standard frequency by a similar relationship.

$$(9) \qquad f_s = \frac{N}{T}$$

Solving equations (8) and (9) simultaneously for f_p and substituting the result into equation (3) one obtains

$$(10) \qquad H = 23.4868 \frac{n f_s}{N}$$

As the period of count is measured in finite intervals, i.e., the period of one cycle of the standard frequency, the smaller these intervals are, the more precise the measurement of the period of count and thus the field intensity H. To make the interval of measurement smaller, the standard frequency must be made higher.

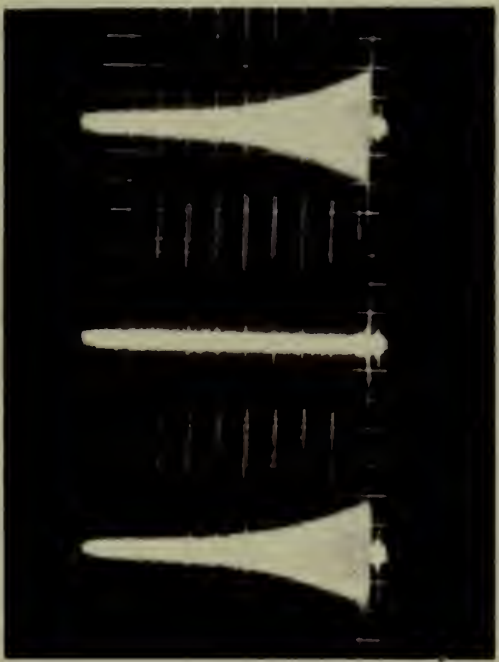
The fast counter is a binary counter that is used to count the cycles of the standard frequency. The oscillator that generated the standard frequency for this experiment ran at 800 kc/s, rather than at 100 kc/s which is normal for the production models of the Airborne Magnetometer. It was hoped that the higher standard frequency would allow greater accuracy in measuring the Earth's magnetic field.

4.0 Experimental Results.

When the Nuclear Free Precession Magnetometer with Overhauser Enhancement was first made to operate in Method 3, it was found that the output signal was as good or better than that for a Nuclear Free Precession Magnetometer using normal polarization. Figure 13 shows the signals for both the normal and Overhauser version of the magnetometer. In normal operation it took approximately five amperes of polarizing current to produce this output signal. The polarization field required 400 microfarads for critical damping.

The signal from the magnetometer with Overhauser enhancement was run with about 400 volts on the plates and drawing 100 milliamperes plate current. This provided about 20 watts into the load. Upon measurement of the enhancement field in the sample, it found to be 1.48 gauss. The orientation field was removed without any damping.

Figure 14 shows a graph of the magnitude of the output signal as a function of the magnitude of the orientation current. The current may also be interpreted as the field strength of the environmental field. As may be noted from Figure 14, the peaks in the curve are at 38 and at 77 milliamperes. It may also be seen from Figure 15 that if the relationship between the current and the environmental field is assumed to be correct, then the frequency of the enhancement oscillator must be assumed to be in error. For the frequency determined from the current of the major peak, it is seen that the second peak should occur at 58 milliamperes rather than the 77 milliamperes observed.



0.2 v/cm verticle, 0.1 ms/cm horizontal
30 ma orienting current
59 mc/s enhancement frequency

same as above except enhancement
oscillator shut off.

As straight magnetometer
5 amperes of polarizing current.

FIGURE 13 PICTURE OF OUTPUT SIGNALS

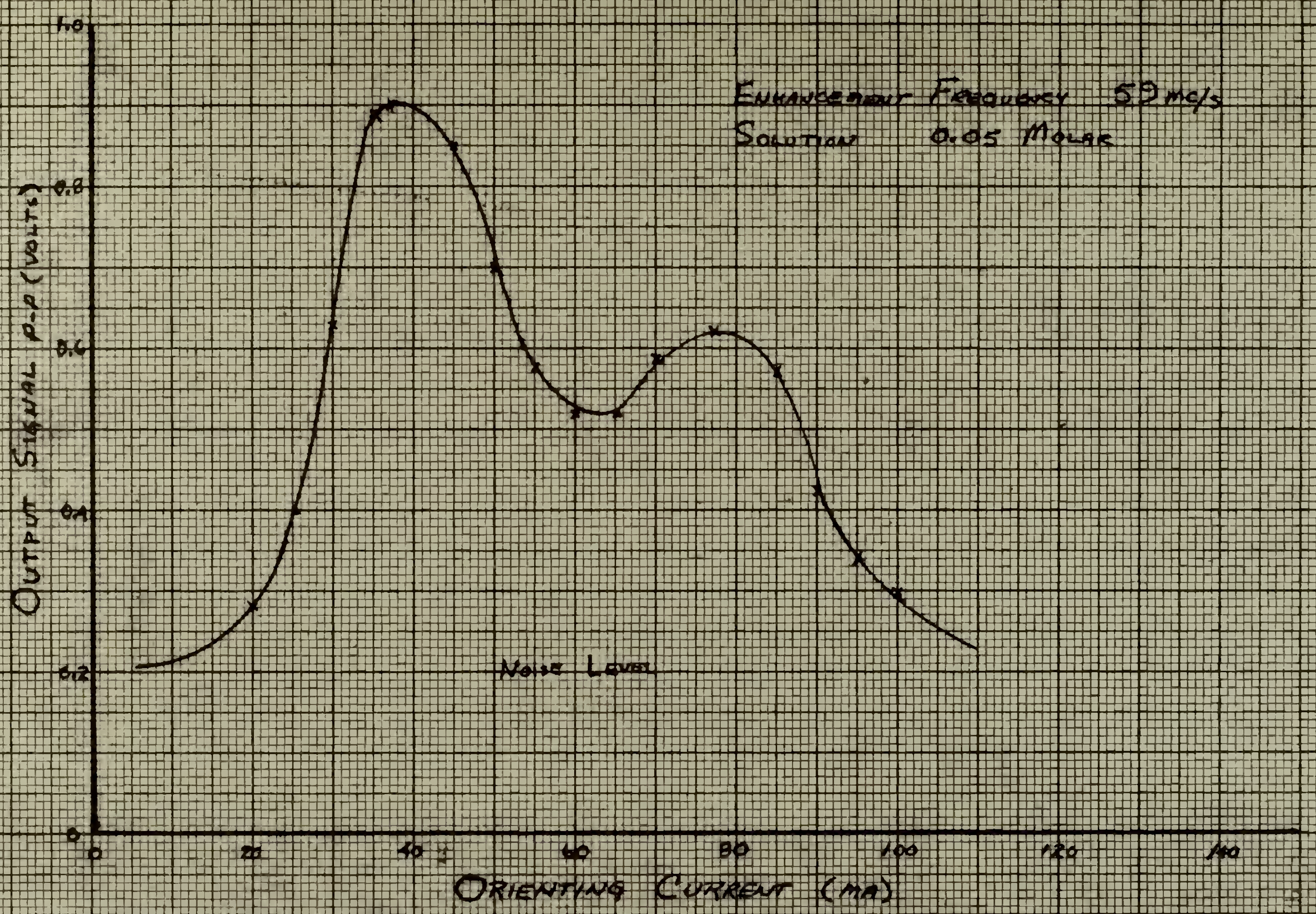


Figure 14 Plot of Output Signal Magnitude vs Orienting Field Current

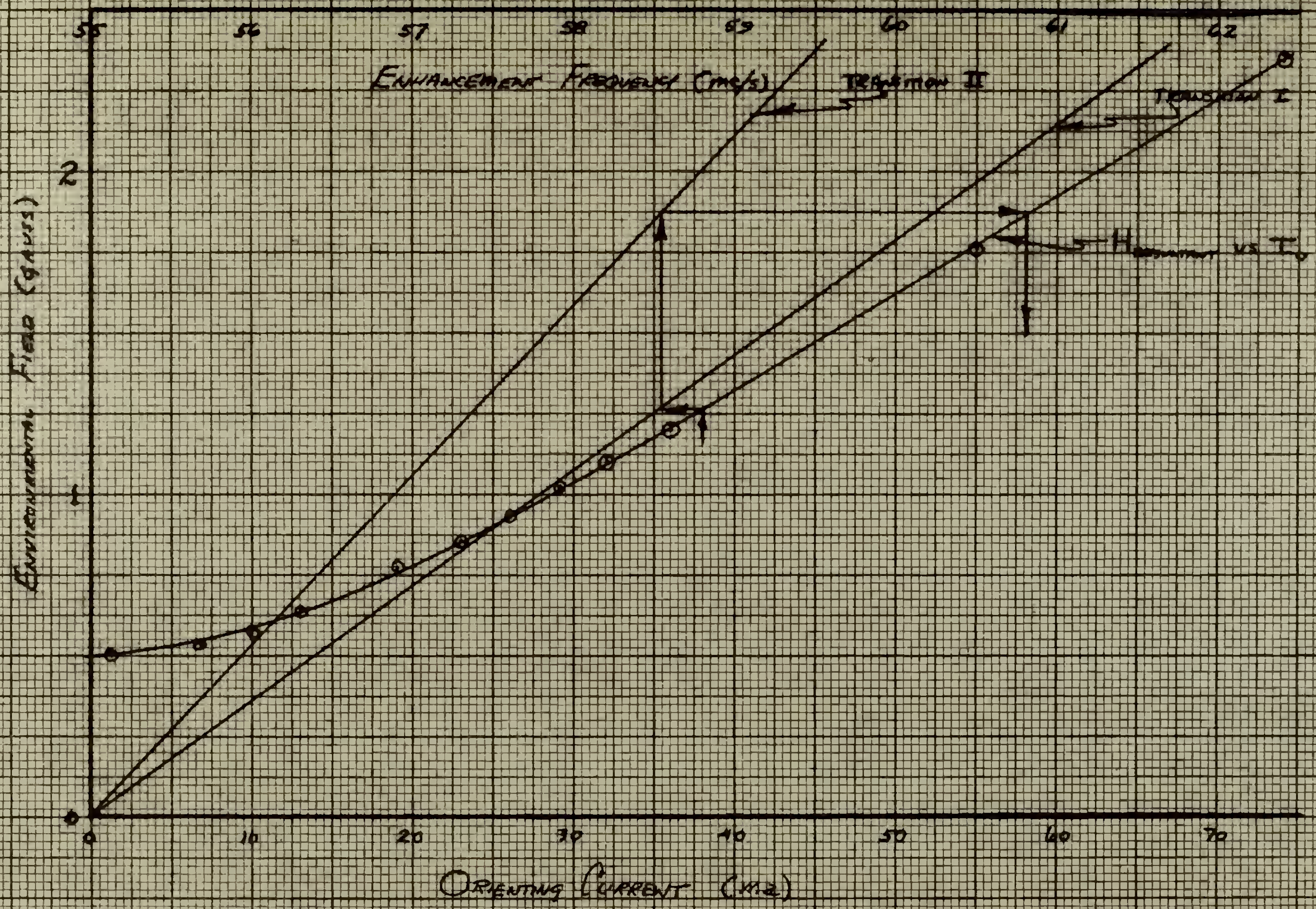


FIGURE 15 OPERATING CURVES OF ENHANCEMENT FREQUENCY VS ORIENTING FIELD CURRENT

Figure 16 shows the relationship of the magnitude of the output signal as a function of the duration of enhancement. This curve was taken with the enhancement oscillator plate voltage at 600 volts and drawing about 170 milliamperes. This produced a radio frequency field in the sample of about 2.6 gauss. It may be seen that the duration of enhancement is not a linear relationship to signal magnitude but appears rather to be an exponential relationship as might be expected when considered in relation to T_1.

Figure 17 shows a graph of the Earth's magnetic field strength as a function of time. This graph was taken with the magnetometer running at a cycle period of one second. It may be seen that the reliability of the magnetometer is about plus or minus three and one half gamma. This was considered better than average for the location of the detection coils, as there was considerable noise present that could not be removed.

Figure 18 shows the relationship of the colorometric density to the life time of the sample. As the sample breaks down due to chemical reactions, the color normally associated with the fresh sample disappears and the sample becomes colorless. Llyode states that when he was first working with the compound, he found that the chemical breakdown occurred within 30 seconds with an unbuffered solution. Later, he learned to buffer the solution to a ph of 11. This retarded the chemical reaction so that the sample life was in the order of days. It was found by this investigation that the lower the temperature that the sample was maintained at, the longer the sample life. When the samples were not in use, they were frozen and could be retained in this manner as long as one month.

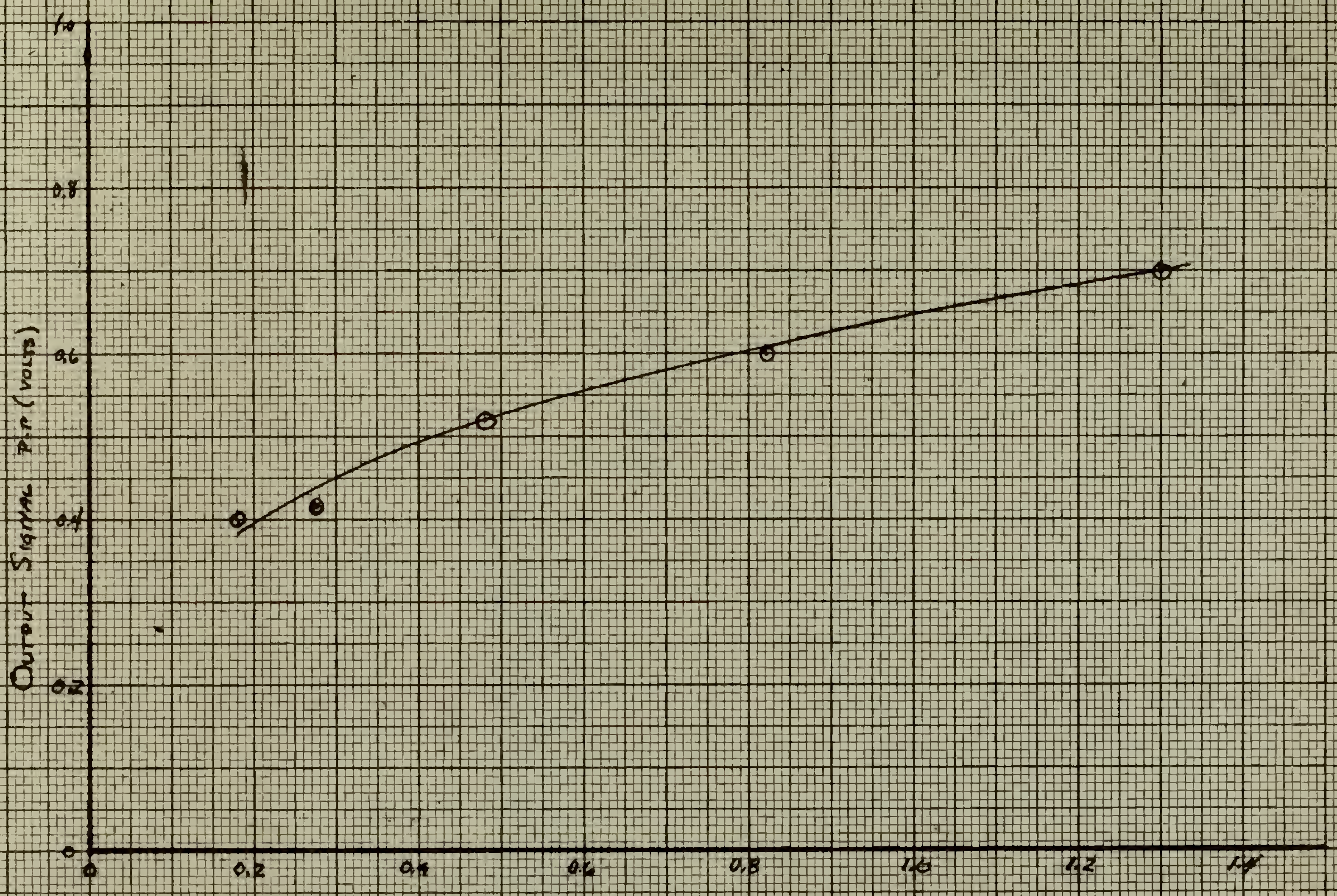


Figure 16 - Plot of Output Signal Magnitude vs Duration of Enhancement

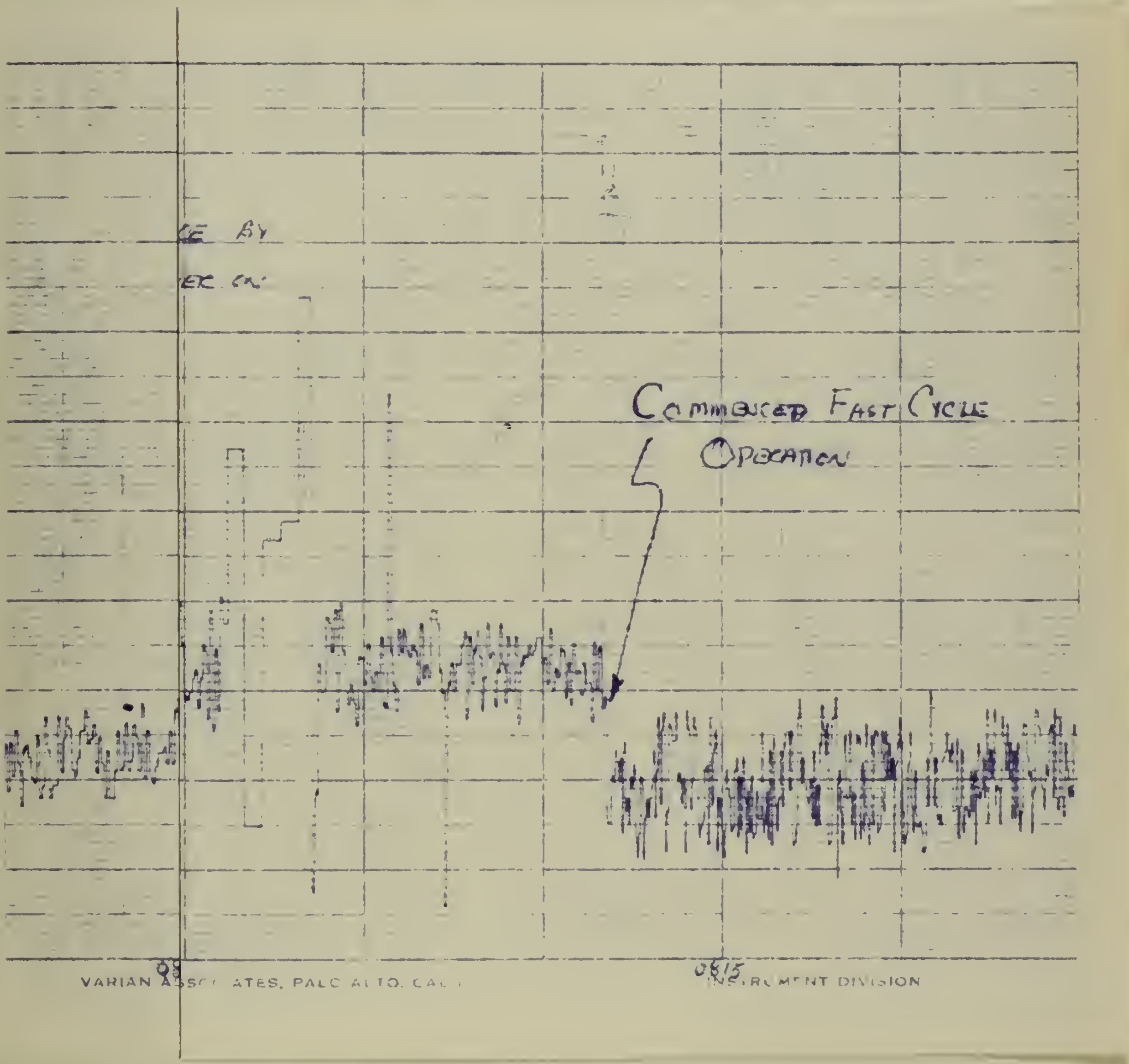


Figure 17 Strip Recording of Earth's Field Strength

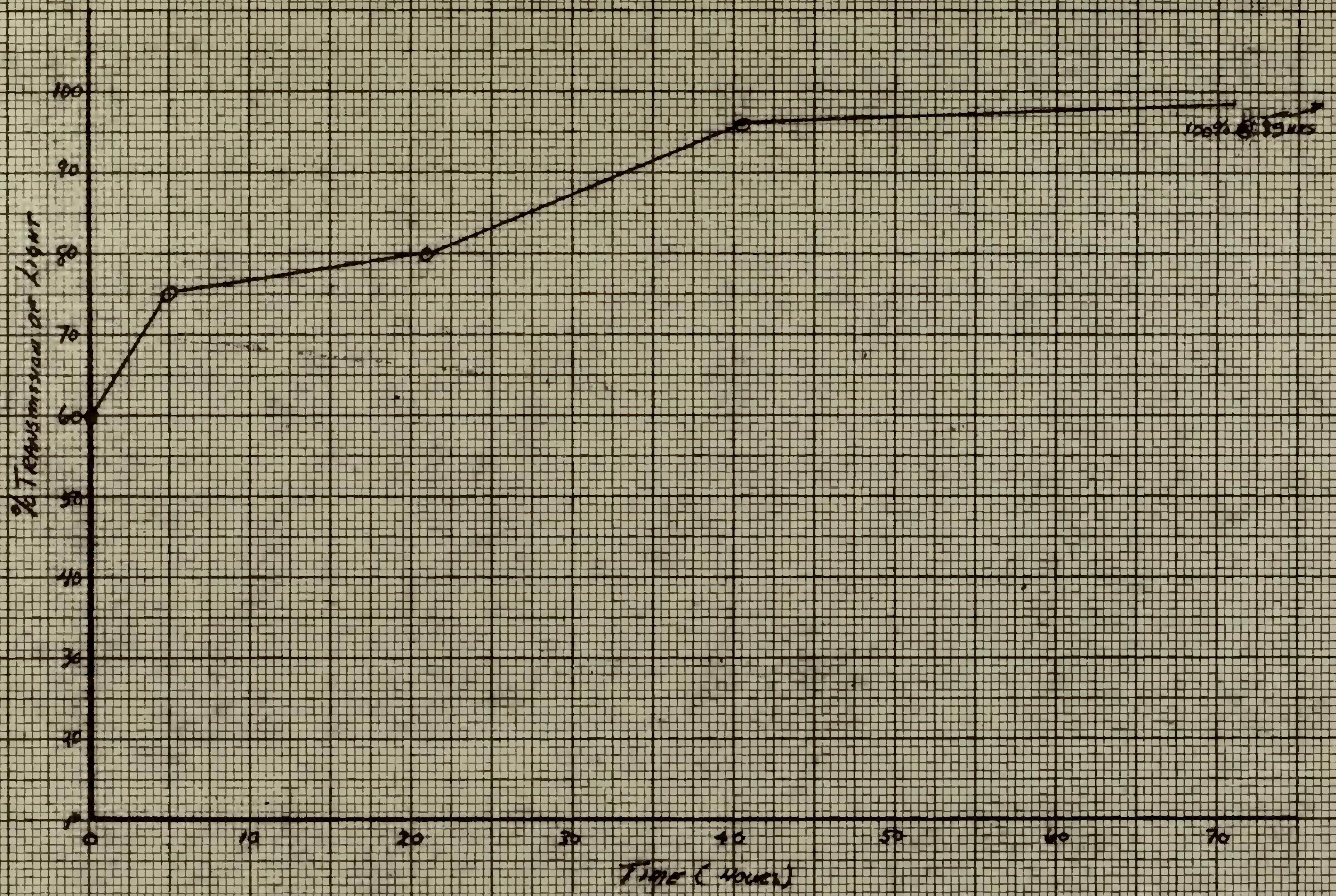


FIGURE 18 PLOT OF COLORIMETRIC DEXTRIN VS TIME

The sample that was kept for one month was kept at about 20 degrees Farenheit, and it therefore appears that the temperature is not critical as long as it is below freezing. The sample breakdown may be accelerated by raising the temperature of the sample. As may readily be seen, when approximately 20 to 80 watts are being put into the sample, if the power is not removed it must be dissapated by raising the temperature of the sample. One sample was ruined in less than ten minutes by running the enhancement oscillator continuously and allowing the sample to approach the boiling point.

It was found that when running Method 3 the orienting current power supply was not necessary. As the ground wire was common to all of the circuits, it had about 1.4 amperes of direct current running thru it. It was found that if the orienting coil were connected in parallel to the ground return wire, about one eighth of the total current or about 200 milliamperes would return thru the coil. By placing a variable resistance in series with the orienting coil when connected in parallel to the ground return wire, the current could be varied from about ten to 100 milliamperes, which was all that was required to operate the magnetometer.

Operation by Method 2 was attempted but with negative results. An audio oscillator was used as the tipping coil signal source and this was kept at the correct frequency by observing the picture on an oscilloscope and comparing the detected Larmor frequency on the horizontal axis and the audio oscillator on the vertical axis. These were intermittant checks as the magnetometer could not be made to run in Method 2 and therefore it had to be shifted to Method 3 occasionally to obtain the Larmor output signal frequency.

5.0 Conclusions.

It is felt that Method 1 is impractical because of one of the restrictions placed on the original Nuclear Free Precession Magnetometer. This is the restriction of critically damping the relatively large current pulses in short intervals. As this method would have required a several hundred milliampere pulse in the order of several microseconds duration, it is felt that these are definite restrictions.

Method 2 offered better conditions for the removal of the tipping pulse. However, this method introduced an additional parameter, frequency, that was open to objection. The fact that the frequency had to be known, stored, and used to tune an audio frequency oscillator caused additional equipment to be built and integrated into the system. The additional time required to operate the tipping coils lengthened the period of the cycle and thus is not desirable.

It is felt that from a standpoint of complexity and increased cycle period, both Methods 1 and 2 are not feasible.

Method 3 offered the most desirable system for the operation of the Nuclear Free Precession Magnetometer with Overhauser Enhancement. The simplicity of the system in itself is most welcome. There was no increase in cycle period due to secondary operations. Both the operations of population increase and orientation were accomplished at the same time. Equipment was kept simple, requiring only the addition of the enhancement oscillator and it's power supply. The power supply for the enhancement oscillator would replace the power supply required for the polarizing curent in the normal magnetometer and could be done on a pound for pound basis, if not better.

One objection that is raised to the Nuclear Free Precession Magnetometer with Overhauser Enhancement is the fact that the chemical used to gain the desired population difference is unstable at room temperature. With a usable life time measured in days, it could prove a costly procedure to replenish the sample solution this rapidly.

It is felt that the Nuclear Free Precession Magnetometer with Overhauser Enhancement is a useful addition to the magnetometer family and will be especially important when the large fields generated by the normal Nuclear Free Precession Magnetometer are objectionable.

BIBLIOGRAPHY

1. F. Block, W. W. Hansen, and M. Packard; Phys. Rev. 69 127, 1946.

2. E. M. Purcell, J. C. Torrey, and R. V. Pound; Phys. 4ev. Phys. Rev. 69, 37, 1946

3. F. Block; Phys. Rev. 70, 460, 1946

4. H. A. Thomas, R. L. Driscol, and J. A. Hipple; NBS, RP 2104 Vol. 44, June 1950, Phys. Rev. 78, 787, 1950

5. A. Abragam, J. Combrisson, and I. Solomon; Comp. Rendes, 8 July 1957, 157

6. N. Bloemberger; Phys. Rev. 104, 324, 1956

7. H. Kastler; Phys. Soc. London; A67, 853, 1954

8. M. Packard and R. Varian; Phys. Rev. 93, 941, 1954

9. T. L. Allen and M. Packard; The Varian Free Precession Magnetometer

10. G. E. Pake; Scientific American, Aug. 1958, Magnetic Resonance

11. Varian Assoc. NMR Spectrometry Lecture Notes

12. Varian Associates; Model V4910 Proton Free Precession Airborn Magnetometer

13. E. H. Rogers; NMR and EPR - Their Principles and Instrumentation

14. W. E. Bell; Magnetoabsorption

15. J. M. Drake; The Varian M-49 Portable Proton Free Precession Magnetometer

16. A. L. Bloom and M. Packard; Science, Vol. 122, pp. 738-741, 1955

17. R. V. Pound and W. D. Knight; Rev. Sci. Instr. 21 219, 1950

18. C. H. Bowen; Thesis, USNPS, An Earth's Field Magnetometer that Utilizes the Free Precession of Protons

19. J. P. Lloyd and G. E. Pake; Phys. Rev. 94, 579, 1954

20. A. L. Bloom and W. E. Bell; Private Correspondence

BIBLIOGRAPHY

21. H. Y. Carr and E. M. Purcell; Phys., Rev. 94, 630, 1954

22. E. L. Hahn; Phys. Rev. 80, 580, 1950

23. G. E. Pake; Am. J. Phys. 18, 438, 1950

APPENDIX A

Calculations of Tipping Field Strength and Duration

For the Tipping Coil

$$H = 15.2\, I$$

As it is desired to leave only 90° of rotation

$$\omega \tau = \pi/2$$

$$H = \frac{23.4868 \times 10^{-5}}{2\pi}\, \omega$$

$$\therefore \tau I = \frac{23.4868 \times 10^{-5}}{4\,(15.2)}$$

$$= 3.87 \times 10^{-6} \text{ ampere seconds}$$

$$= 3.87 \text{ micro ampere seconds}$$

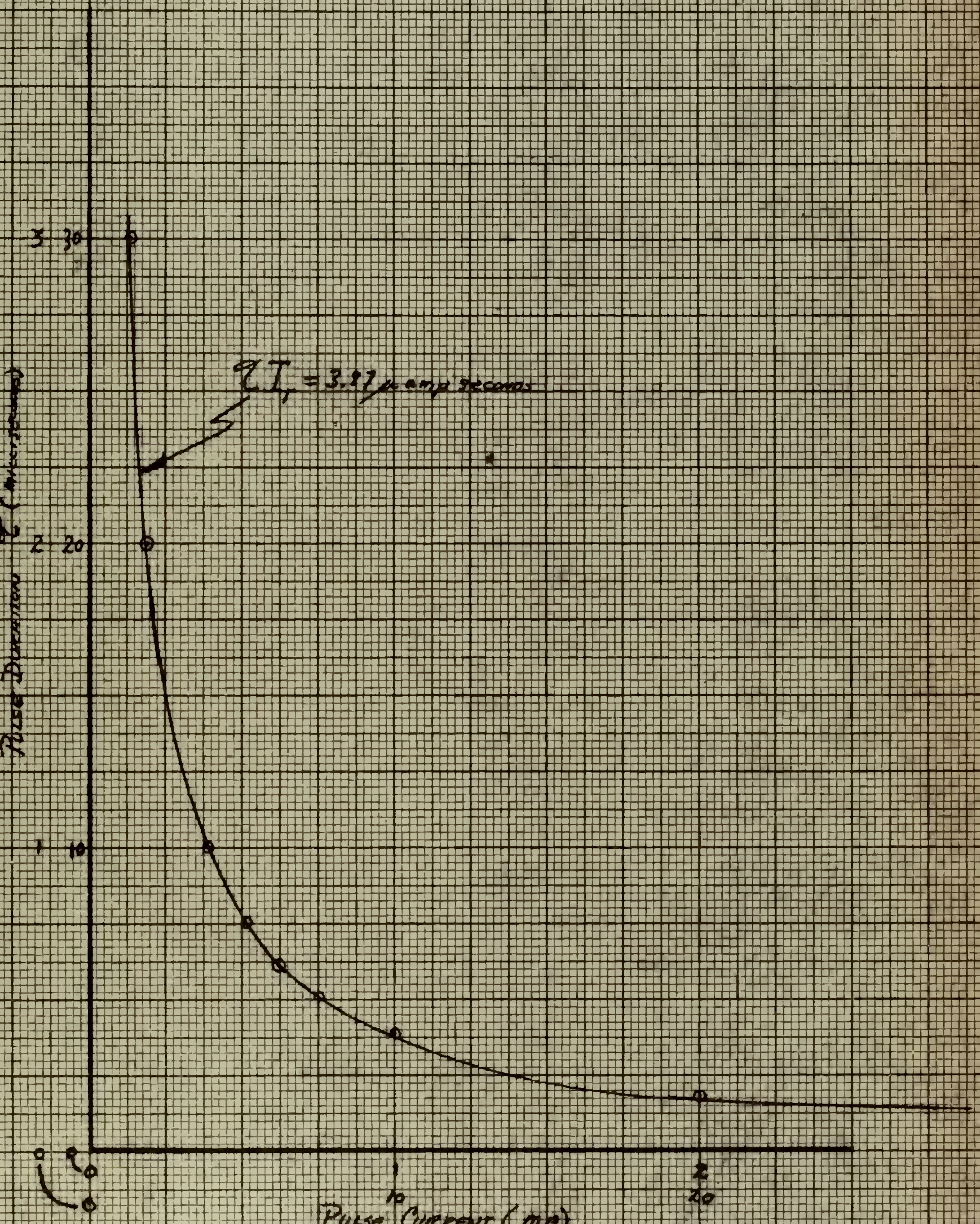
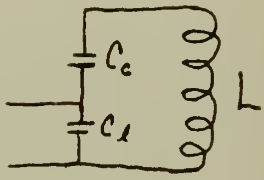


FIGURE 19 CALIBRATION CURVE FOR TIPPING FIELD

APPENDIX B

Calculations for Matching Enhancing

Coil to 50 Ω cable.



$$(12) \quad Z_{in} = \frac{\frac{1}{j\omega C_l}\left(\frac{1}{j\omega C_c} + j\omega L + R\right)}{\frac{1}{j\omega C_l} + \frac{1}{j\omega C_c} + j\omega L + R}$$

At resonance

$$\frac{1}{j\omega C_c} + \frac{1}{j\omega C_l} = j\omega L$$

$$(13) \quad \therefore Z_{inR} = \frac{\frac{1}{j\omega C_l}\left(-\frac{1}{j\omega C_l} + R\right)}{R}$$

$$= \frac{1}{\omega^2 C_l^2 R} + \frac{1}{j\omega C_l}$$

Ignoring the second term as small

$$(14) \quad Z_{in} = 50\,\Omega = \frac{X_{cl}^2}{R}$$

$$R = \frac{\omega L}{Q} = \frac{100}{40} = 2.5 \text{ UNLOADED}$$

$$= \frac{40}{26} = 1.54 \text{ LOADED.}$$

$$(15) \quad X_{cl}^2 = 77$$

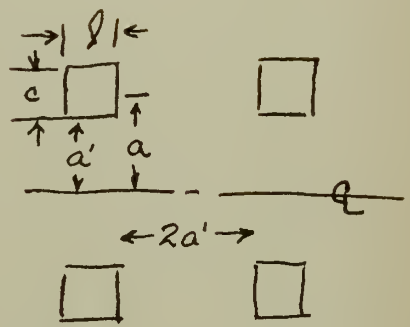
$$X_{cl} = 8.75\,\Omega$$

$$C_l = 175\,\mu\mu f \text{ at } 55 \text{ mc/s}$$

Design of Tipping Coils

From RadioTron Designers Handbook

$$(16)\quad L = \frac{aN^2}{13.5}\log_{10}\frac{4.9a}{l+c}\ \mu h$$



Assume

$N = 400$ turns, 20 turns per layer, 20 layers

$l = c = 1.2''$ for 20 turns of #15 enameled copper wire

$a = a' + c/2$

$a' = 6/2''$

$a = 6/2 + 1.2/2 = 3.6''$

$$L = \frac{3.6(400)^2}{13.5}\log_{10}\frac{4.9(3.6)}{2.4}$$

$$= 4.10\times10^4 \log_{10} 7.35$$

$$= 4.10\times10^4 (0.866)$$

$= 3.55\times10^4$ micro henries

$= 35.5$ milli henries

Measured:

$L = 41.37$ mh @ 1000 cps for one coil

$= 82.75$ mh for two coils in series

$Q = 49$

APPENDIX D

Field Strength Calibration of the Detection and Tipping Coils

Equations for Flip Coil.

(17) $E_m = 2\pi f N \phi_m \times 10^{-8}$

(18) $\phi = BA$

(19) $B = \mu H = H$ for $\mu = 1$

(20) $\therefore E_m = 2\pi f N H \frac{\pi D^2}{4} \times 10^{-8}$

H = gauss
E_m = peak volts
f = 60 cps
$N = 5$
$D = 1.25'' = 3.175$ cm
$D^2 = 10.1$ cm^2

(21) $$H = \frac{E_m}{2\pi^2 f N \frac{D^2}{4} \times 10^{-8}}$$

$$= \frac{E_m}{2\pi^2 (60)(5)\left(\frac{10.1}{4}\right) \times 10^{-8}}$$

$$= \frac{E_m}{15.0 \times 10^{-5}}$$

(22) $= 6.66\ E_m = 6.66 E_3$

(23) $= 9.44\ E_{rms} = 9.44\ E_2$

(24) $= 12.33\ E_{pp}$

Equations (22), (23), (24) are plotted in figure 19

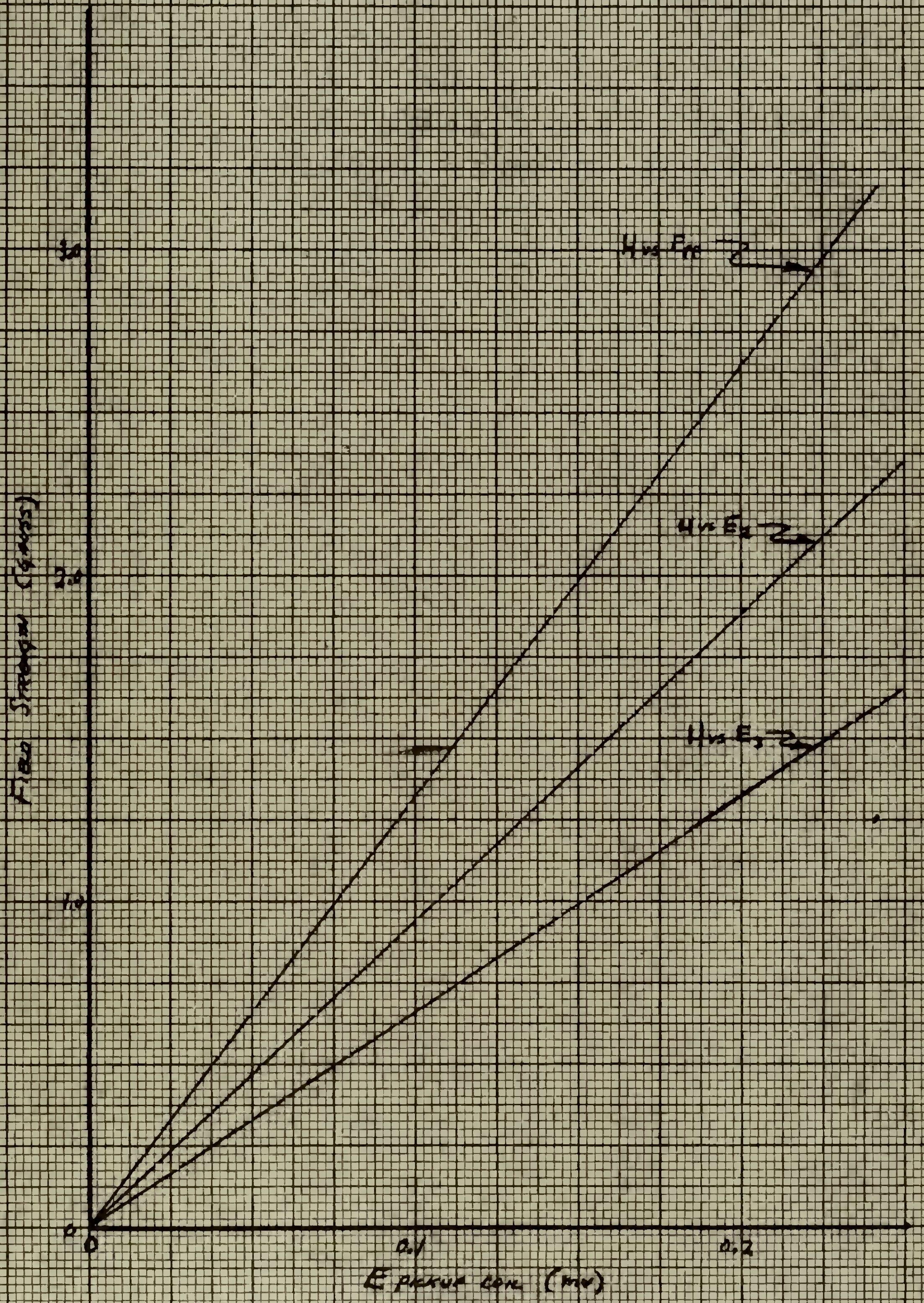


FIGURE 20 CALIBRATION CURVE FOR FIELD INTENSITY FLIP COIL

Detection Coils

I_{peak}	E_z	H	H/I
0.4	1.32	12.4	31.0
1	3.39	31.9	31.9
2	6.8	64.0	32.0

Tipping Coils

I_{peak}	E_z	H	H/I
0.2	0.33	3.15	15.2
0.8	1.235	12.2	15.2
1.0	1.61	15.2	15.2
2	3.22	30.35	15.2

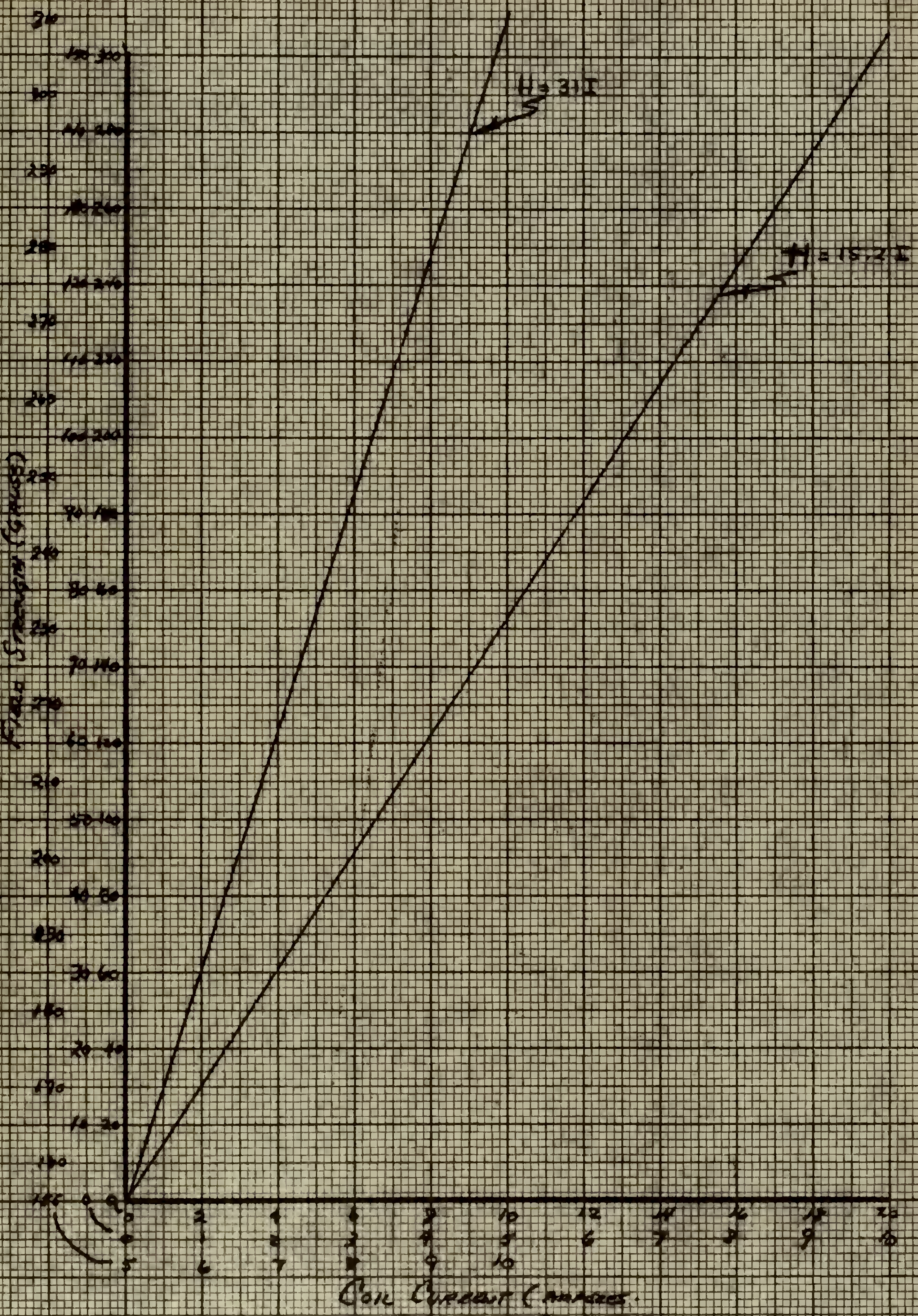
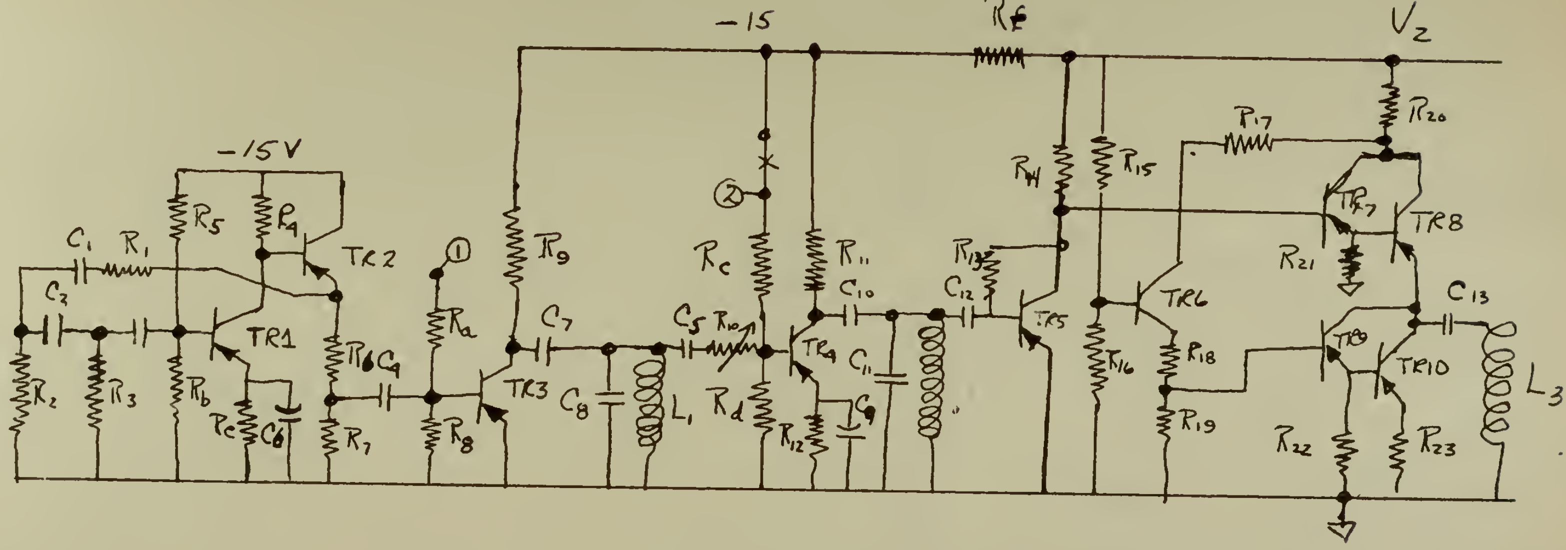


Figure 21 Calibration Curves for Timing and Detection Coils



R_1	1K	R_{10}	0–10megpot	R_{19}	1K	R_e	220	C_1	0.007μf	C_{10}	0.022μf
R_2	5K	R_{11}	6.8K	R_{20}	1	R_f	to drop V_2 to 15 volts	C_2	0.017μf	C_{11}	to resonate L_2 @ 2180 cps
R_3	5K	R_{12}	3.9K	R_{21}	1K	L_1	20 mh	C_3	0.007μf	C_{12}	0.22μf
R_4	15K	R_{13}	180K	R_{22}	220			C_4	0.22μf	C_{13}	100μf
R_5	120K	R_{14}	4.3K	R_{23}	1	L_2	20 mh	C_5	0.22μf		
R_6	6K	R_{15}	470	R_a	120K			C_6	25μf		
R_7	390	R_{16}	15K	R_b	10K	L_3	Tipping Coils	C_7	0.0022μf		
R_8	10K	R_{17}	220	R_c	120K			C_8	to resonate L_1 @ 2180cps		
R_9	4.7K	R_{18}	5.6K	R_d	10K			C_9	25μf		

① to be connected to control multivibrator
② " " " " " "

FIGURE 22 - **Larmor Frequency Oscillator**

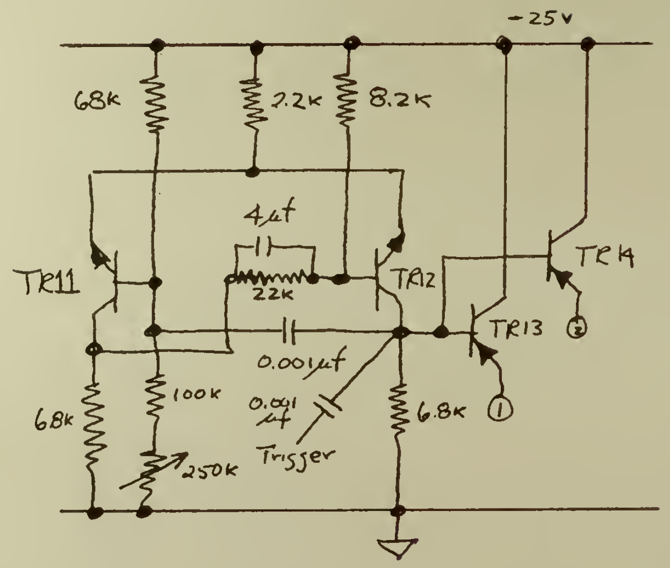


FIGURE 23a

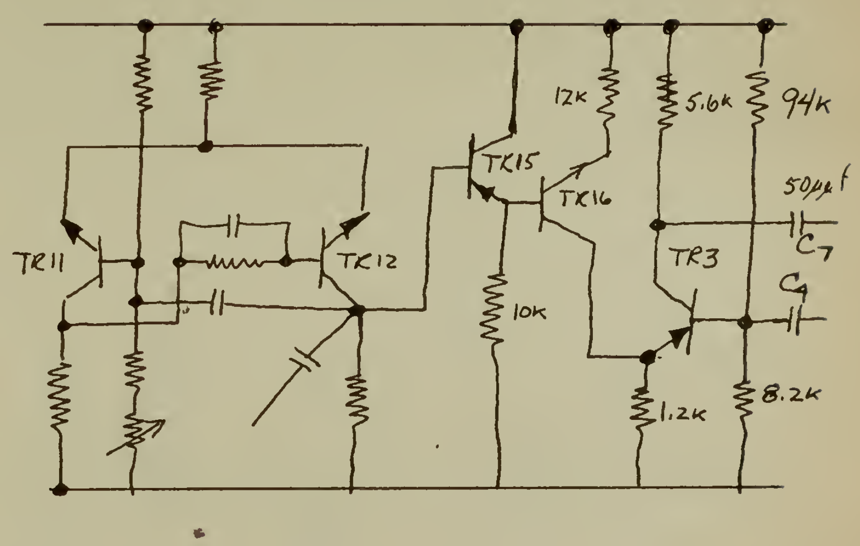
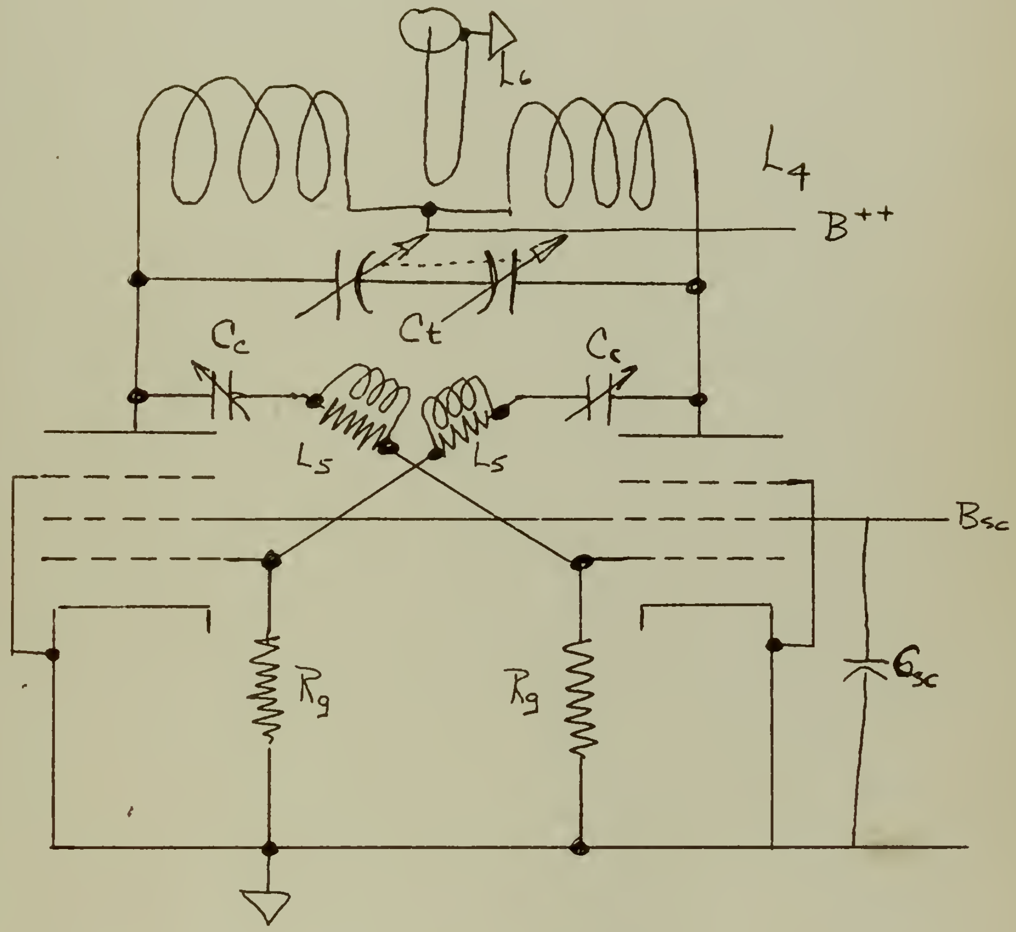


FIGURE 23b

MONO-STABLE MULTIVIBRATOR



C_c 7 $\mu\mu f$ 1000 V
C_t to tune L_4 to f_e
R_g 22K
C_{sc} 0.02 μf

L_4 5 turns 0.1" copper wire 1 1/8" i.d.
L_5 9 turns # 24 copper wire wrapped around 180K 1 watt resistors for parasitic suppression.
L_6 Turn 0.1" copper wire 1 1/8" i.d.

B_{sc} 200V
B^{++} 300 → 600V

FIGURE 2A ENHANCEMENT OSCILLATOR